Intensity Frontier Seminar
FNAL - July 17th, 2014

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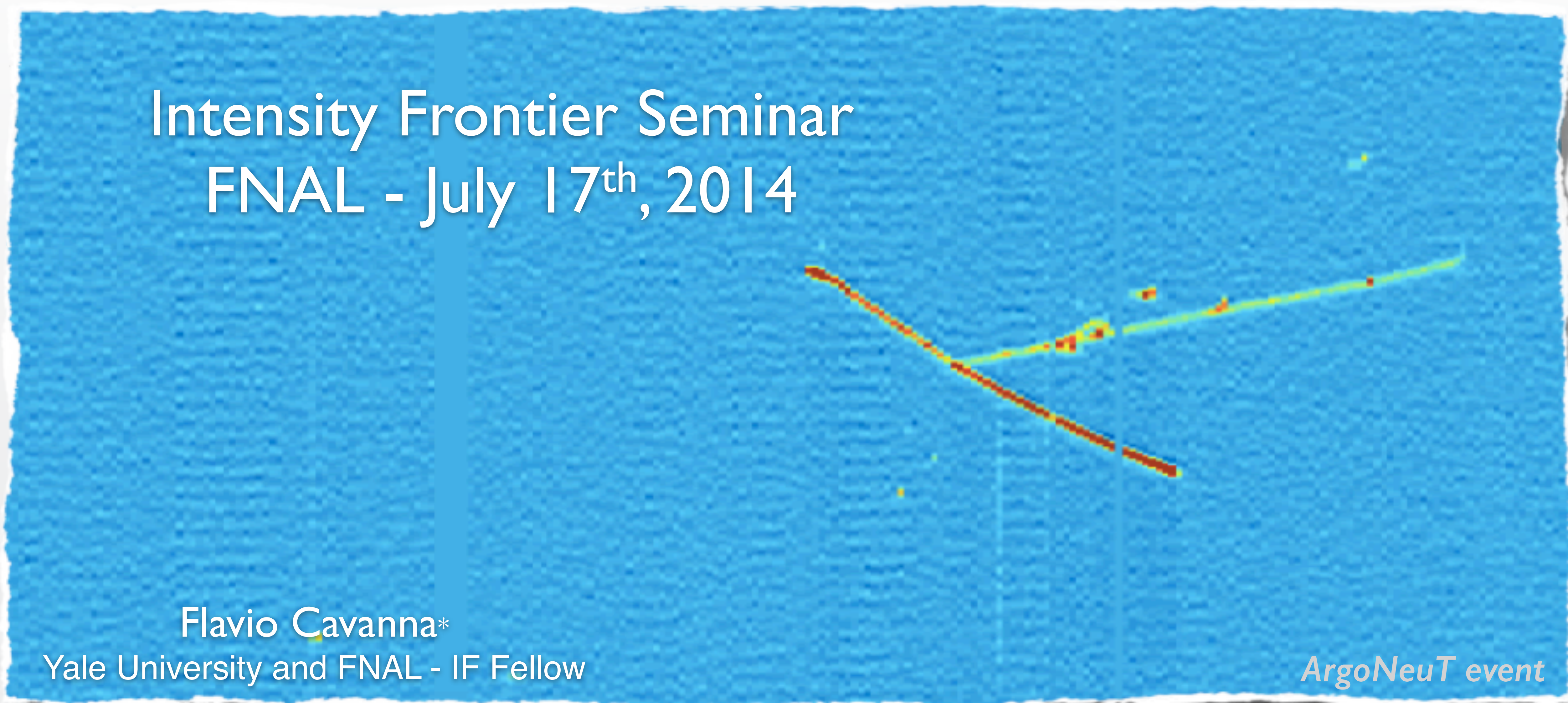
Yale University and FNAL - IF Fellow



Detection of "0-pion" CC neutrino interactions in LArTPC with the ArgoNeuT detector in the NuMI LE beam-line at FNAL:

exclusive cross sections study and topological analysis of the back-to-back proton pairs events.

*on leave of absence from University of L'Aquila, Italy

ArgoNeuT

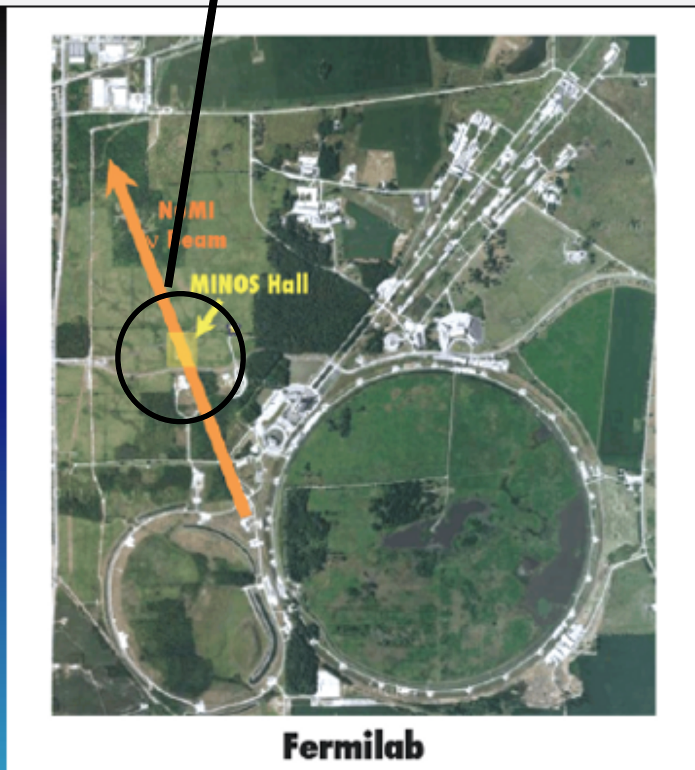
"The ArgoNeuT detector in the NuMI low- energy beamline at Fermilab" JINST 7 P10019 (2012)

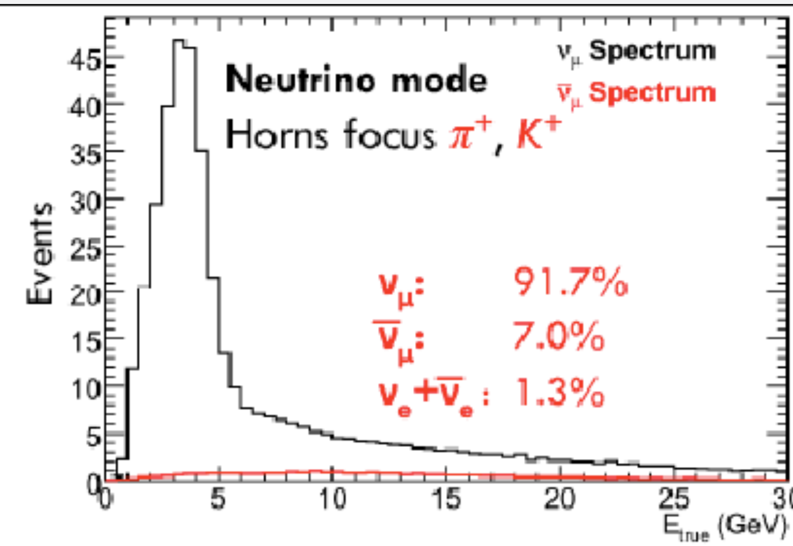
NuMI LE beam
ν−mode (2 weeks):
8.5×10^{18} POT
$\bar{\nu}$−mode (5 months):
1.20×10^{20} POT

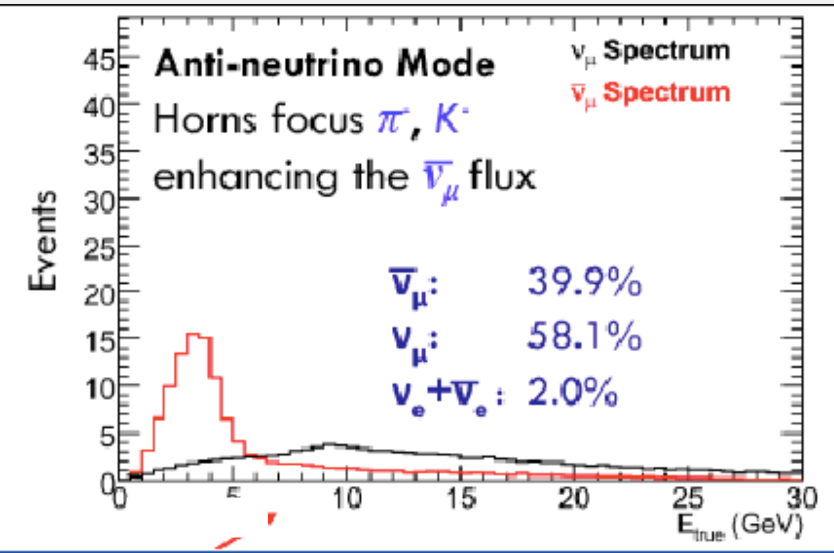
170 l active volume
$47\times40\times90$ cm^3, wire spacing 4 mm
LAr TPC

~7000 CC events collected

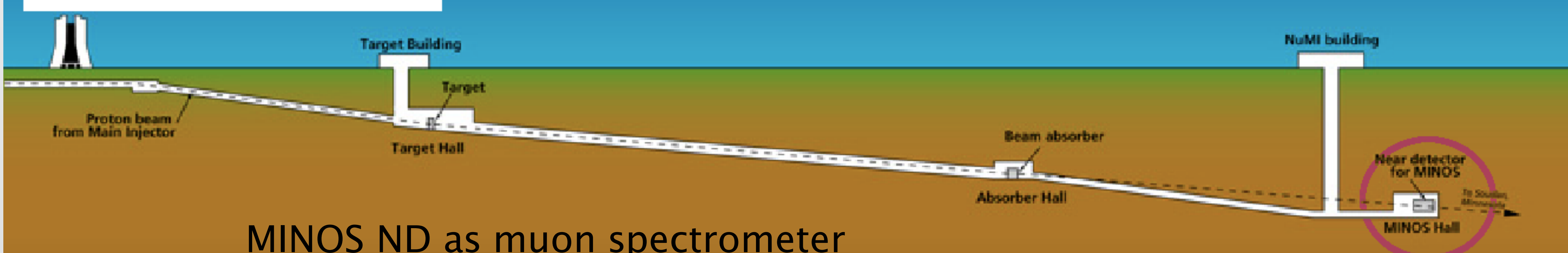
Largest data sample of [low energy] neutrino interactions in LArTPC







NuMI LE beam



MINOS ND as muon spectrometer
for ArgoNeuT events*
(momentum reconstruction and charge identification (q) of exiting muons)

**ArgoNeuT Coll. is grateful to MINOS Coll. for providing the muon reconstruction*

The “new wave” in Neutrino Event Reconstruction

LAr-TPC detectors, providing ***full 3D imaging, precise calorimetric energy reconstruction and efficient particle identification*** allow for **MC independent measurements**, **Exclusive Topology** recognition and **Nuclear Effects exploration**

INSTEAD OF MC BASED CLASSIFICATION OF THE EVENTS IN THE INTERACTION CHANNELS *(QE, RES, DIS etc)*, *CC* NEUTRINO EVENTS IN *LAr* CAN BE CLASSIFIED IN TERMS OF **FINAL STATE TOPOLOGY** BASED ON PARTICLE MULTIPLICITY:

0 pion (**μ+Np,** *where* **N=0,1,2…**), *1 pion* (**μ+Np+1π**) *events, etc..*

EVENT TOPOLOGY: **leading muon accompanied by any number (N=0, 1, 2, 3, 4) of protons final state**

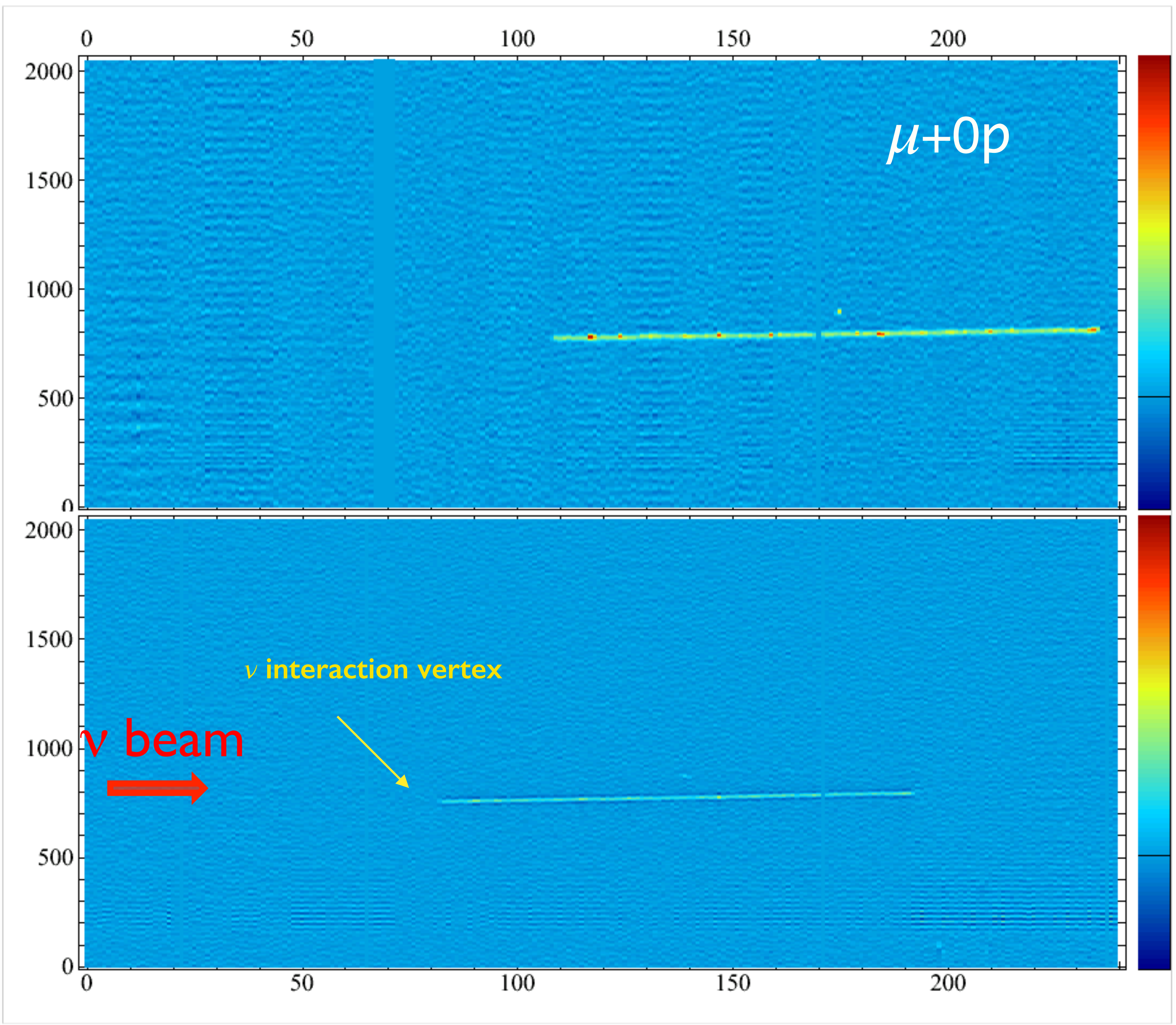
ArgoNeuT ν_μ CC 0 pion topological analysis

Topological characterization of the events:

Count / Id and reconstruct protons at the neutrino interaction vertex*

(low proton energy threshold)

Analysis fully exploiting LAr TPC's capabilities



2D views from the two wire planes

example of $(\mu^+ + 0p)$ events

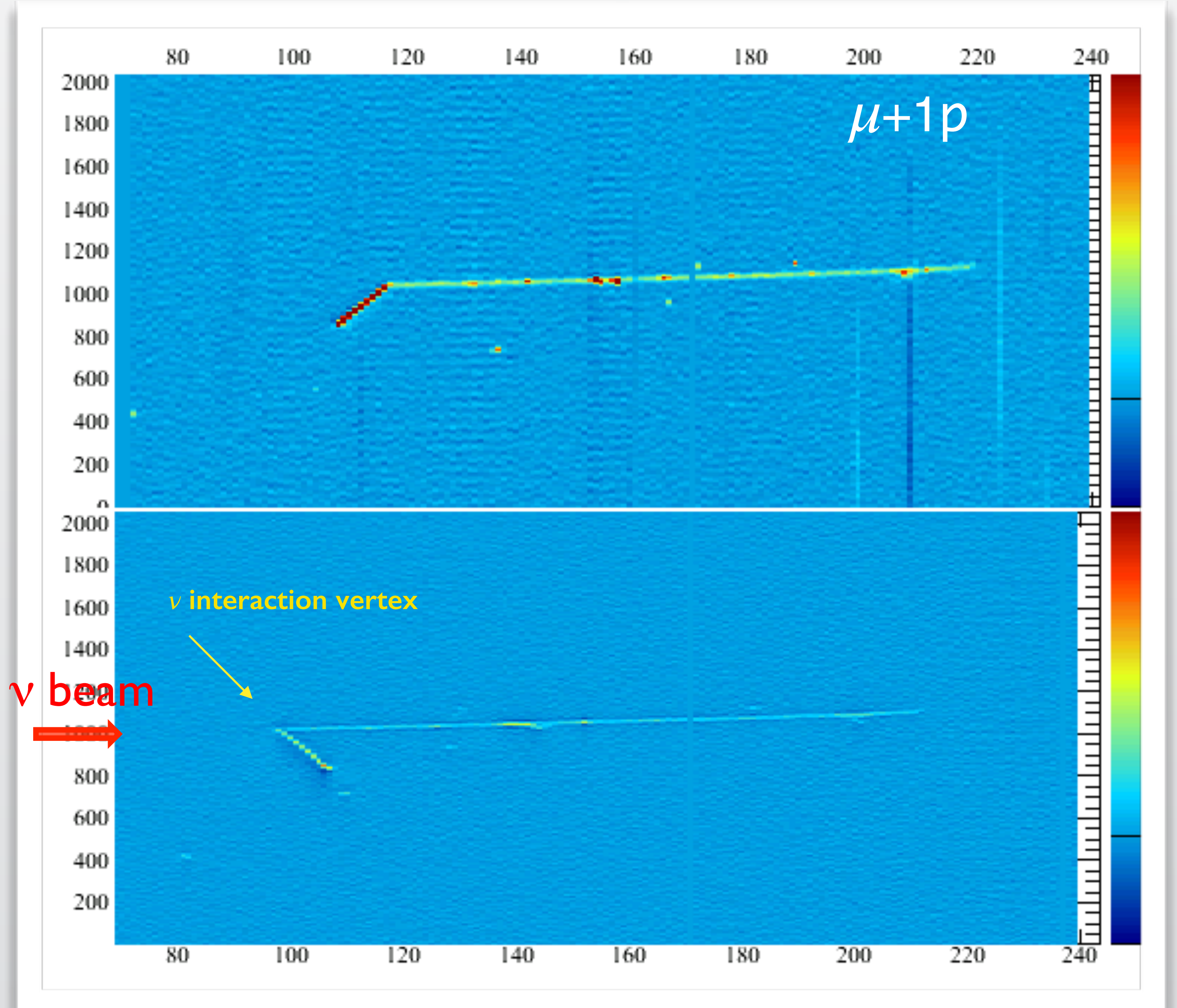
*The muon+Np sample can also contain neutrons. The presence of neutrons in the events cannot be measured, since ArgoNeuT volume is too small to have signicant chances for n to convert into protons in the LAr volume before escaping.

ArgoNeuT ν_μ CC 0 pion topological analysis

Topological characterization of the events: Count / Id) and reconstruct protons at the neutrino interaction vertex

(low proton energy threshold)

Analysis fully exploiting LAr TPC's capabilities



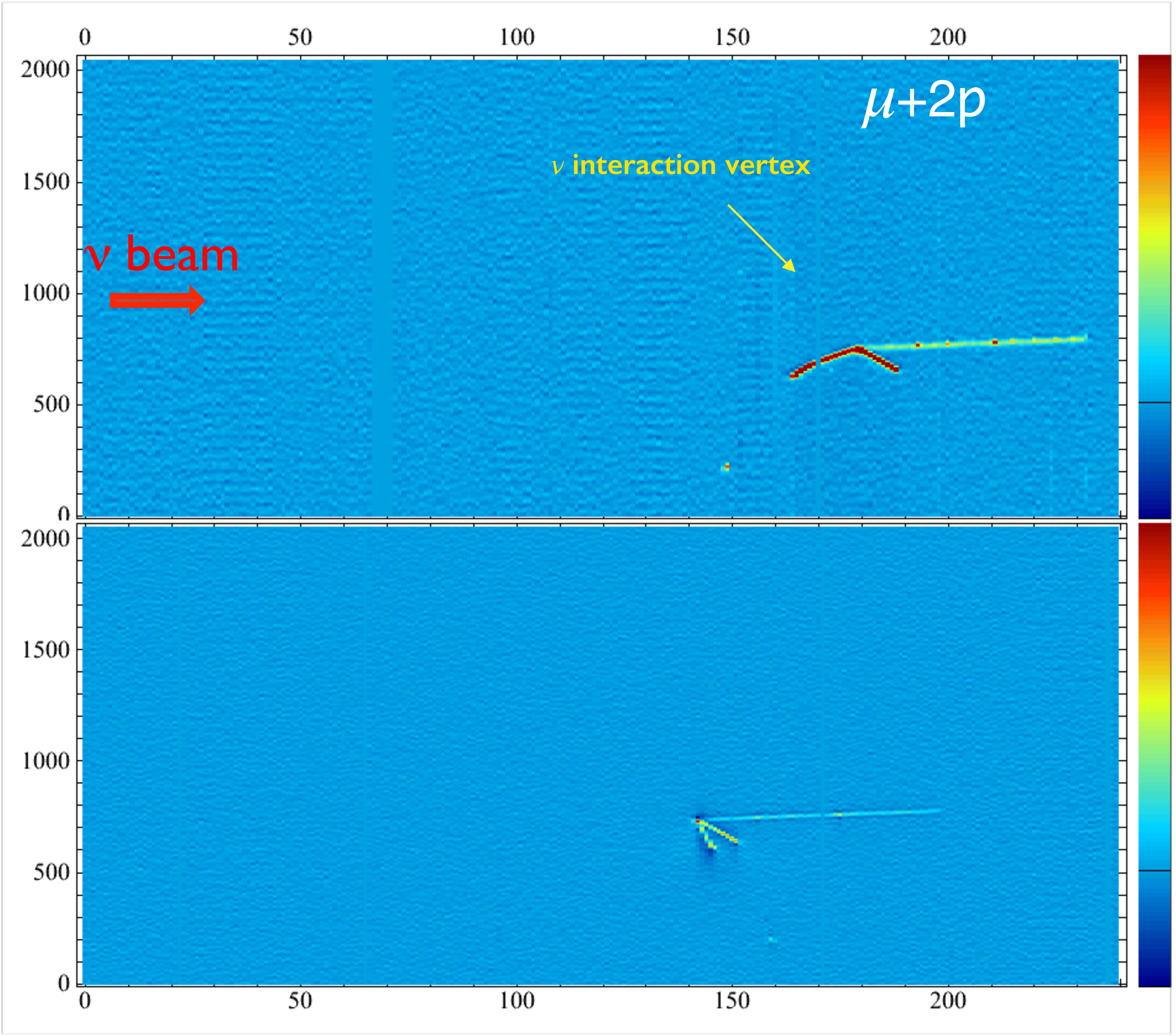
example of $(\mu^+ + 1p)$ events

ArgoNeuT ν_μ CC 0 pion topological analysis

Topological characterization of the events: Count (PId) and reconstruct protons at the neutrino interaction vertex

(low proton energy threshold)

Analysis fully exploiting LAr TPC's capabilities

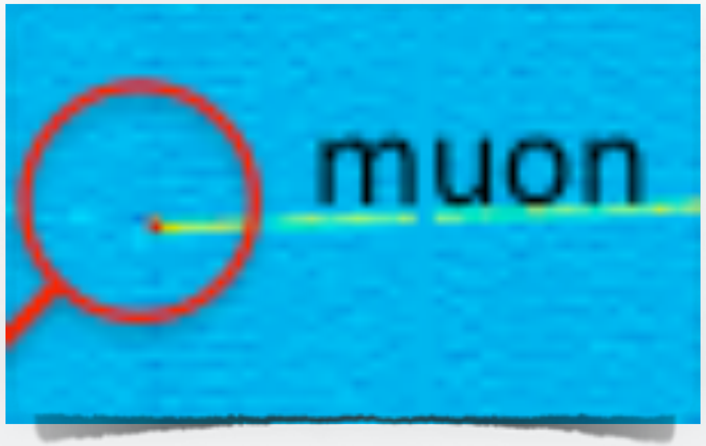


example of
$(\mu^+ + 2p)$
events

Note: *Due to bubble-chamber like quality of LArTPC, visual scanning presents a very powerful tool that allows to learn about features of neutrino interactions that have not been possible to explore with other technologies and existing experiments.*

(ν_μ +Np) events: Primary measurements

- ***Rates of different exclusive topologies*** (proton multiplicities) *with a proton threshold of 21 MeV Kinetic energy*



ν_μ events: ~50% N≠1
$\bar{\nu}_\mu$ events: ~32% N≠0

- ***Muon and proton kinematics*** in events with different proton multiplicity

- Most precise ***reconstruction of the incoming neutrino energy*** from ***lepton AND proton reconstructed kinematics***

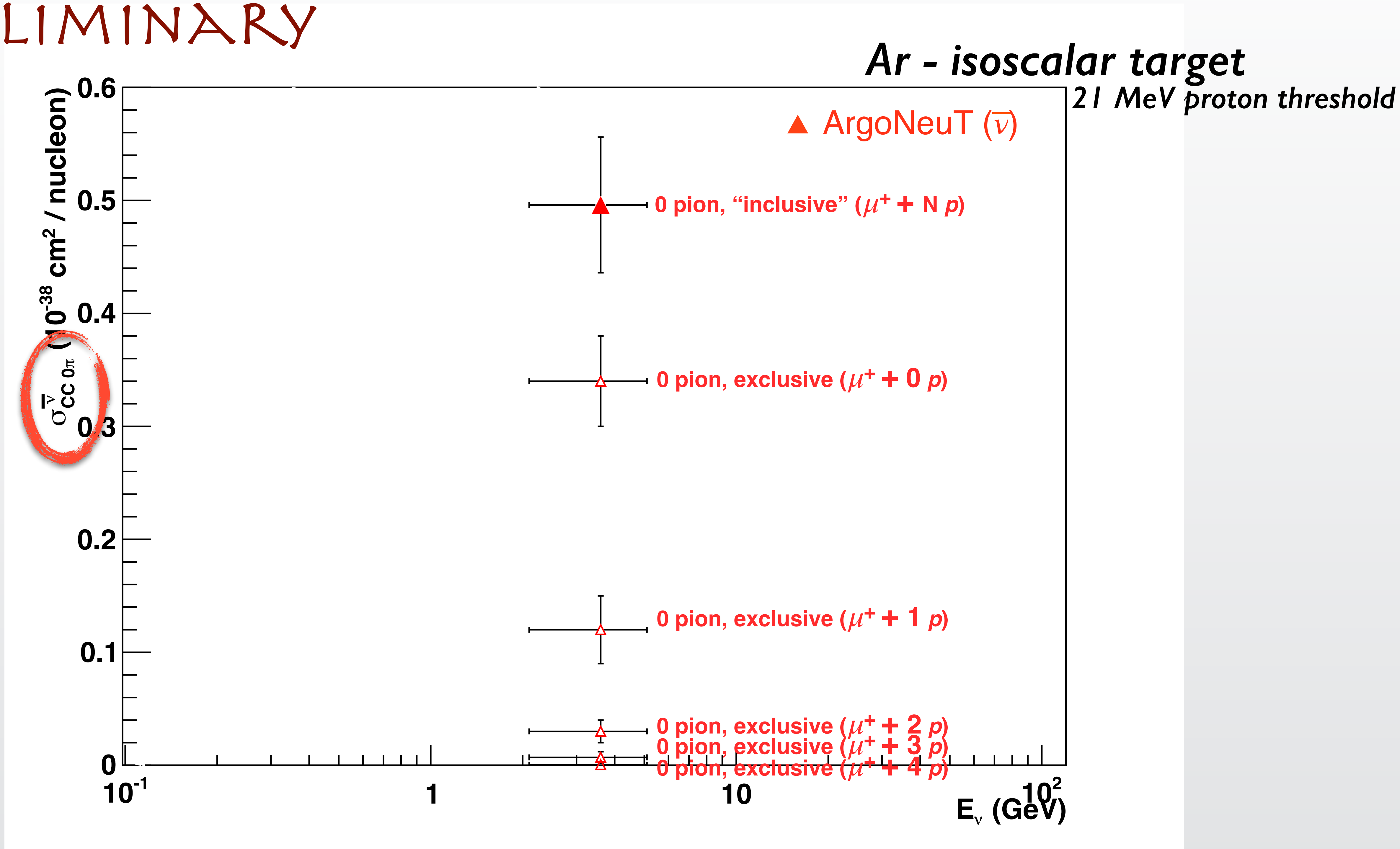
TODAY:

✓ **Anti-neutrino** *CC 0-pion Cross Sections*

✓ **Neutrino interactions**: *Nuclear Effects* from identification and reconstruction of specific classes of events

anti-ν_μ CC 0 pion cross section

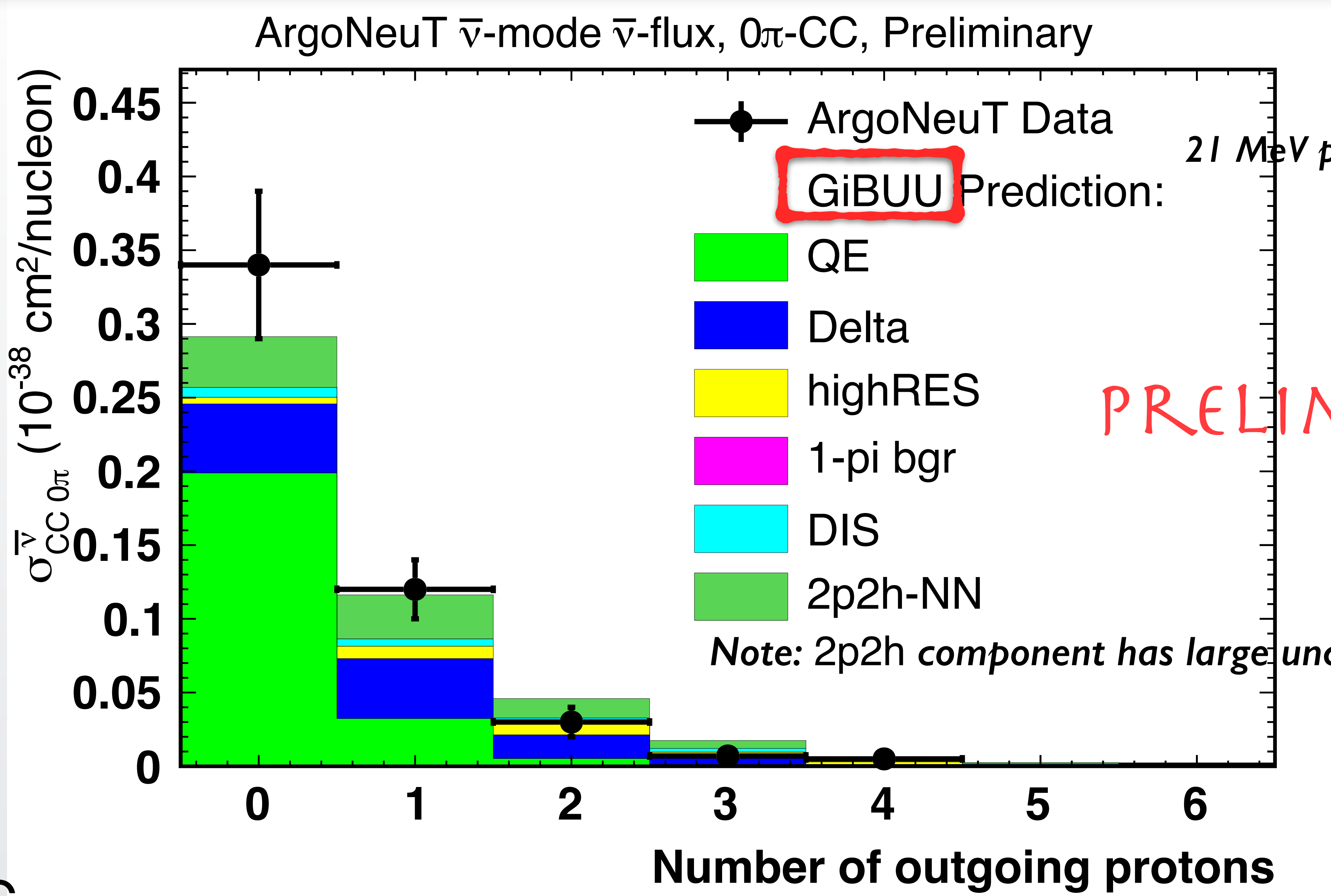
PRELIMINARY



$$\sigma^{\bar{\nu}}_{CC0\pi} = 0.50 \pm 0.03(stat.) \pm 0.06(syst.)\ 10^{-38} cm^2$$

at $\langle E_\nu \rangle$=3.6± 1.5 GeV

anti-ν_μ CC *0-pion* cross section - comparison with GiBUU MC*



GiBUU MC

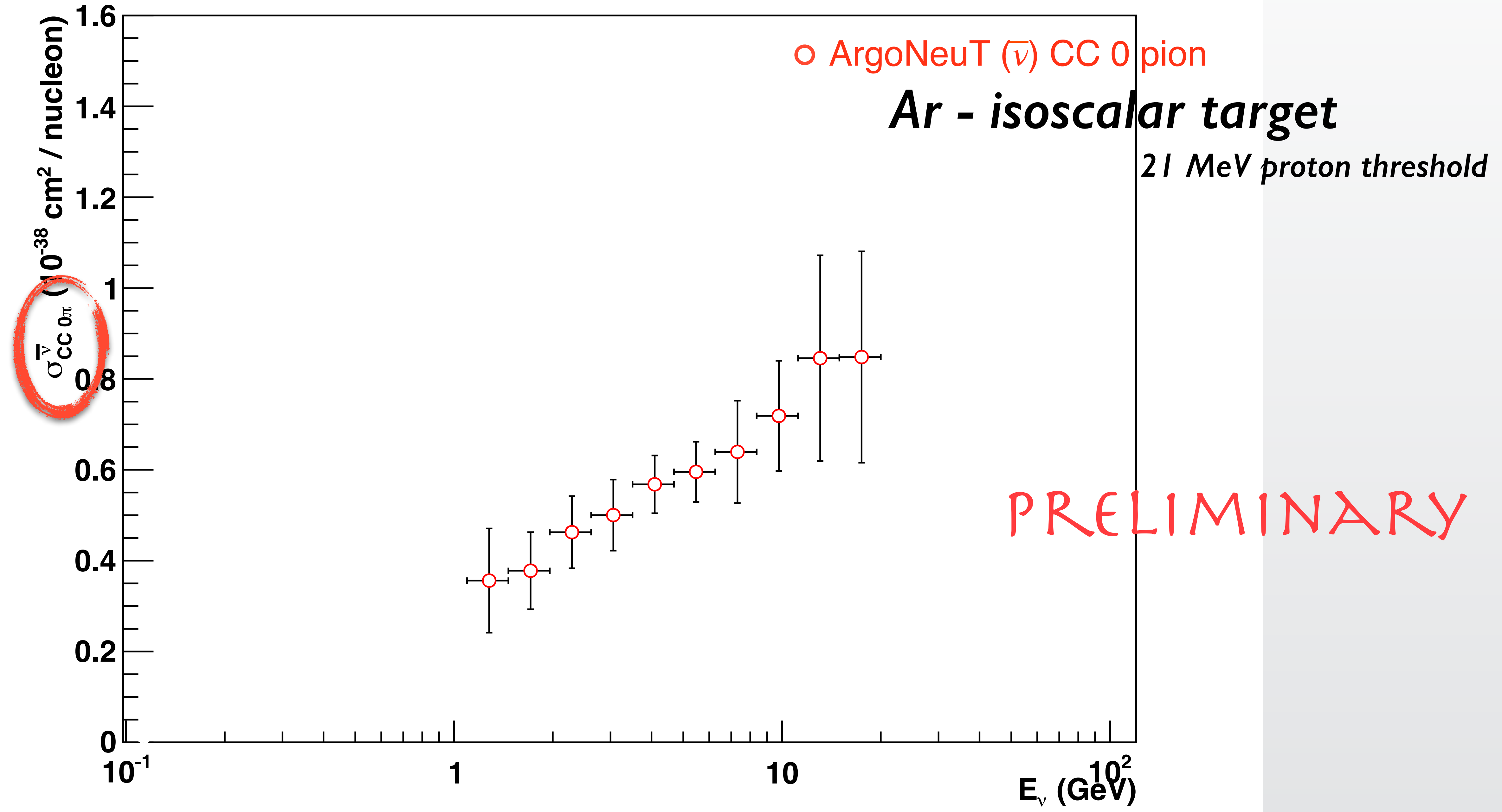
$$\sigma^{\bar{\nu}}_{CC0\pi} = 0.48\ 10^{-38} cm^2/nucleon$$

ArgoNeuT data

$$\sigma^{\bar{\nu}}_{CC0\pi} = 0.50 \pm 0.03(stat.) \pm 0.06(syst.)\ 10^{-38} cm^2$$

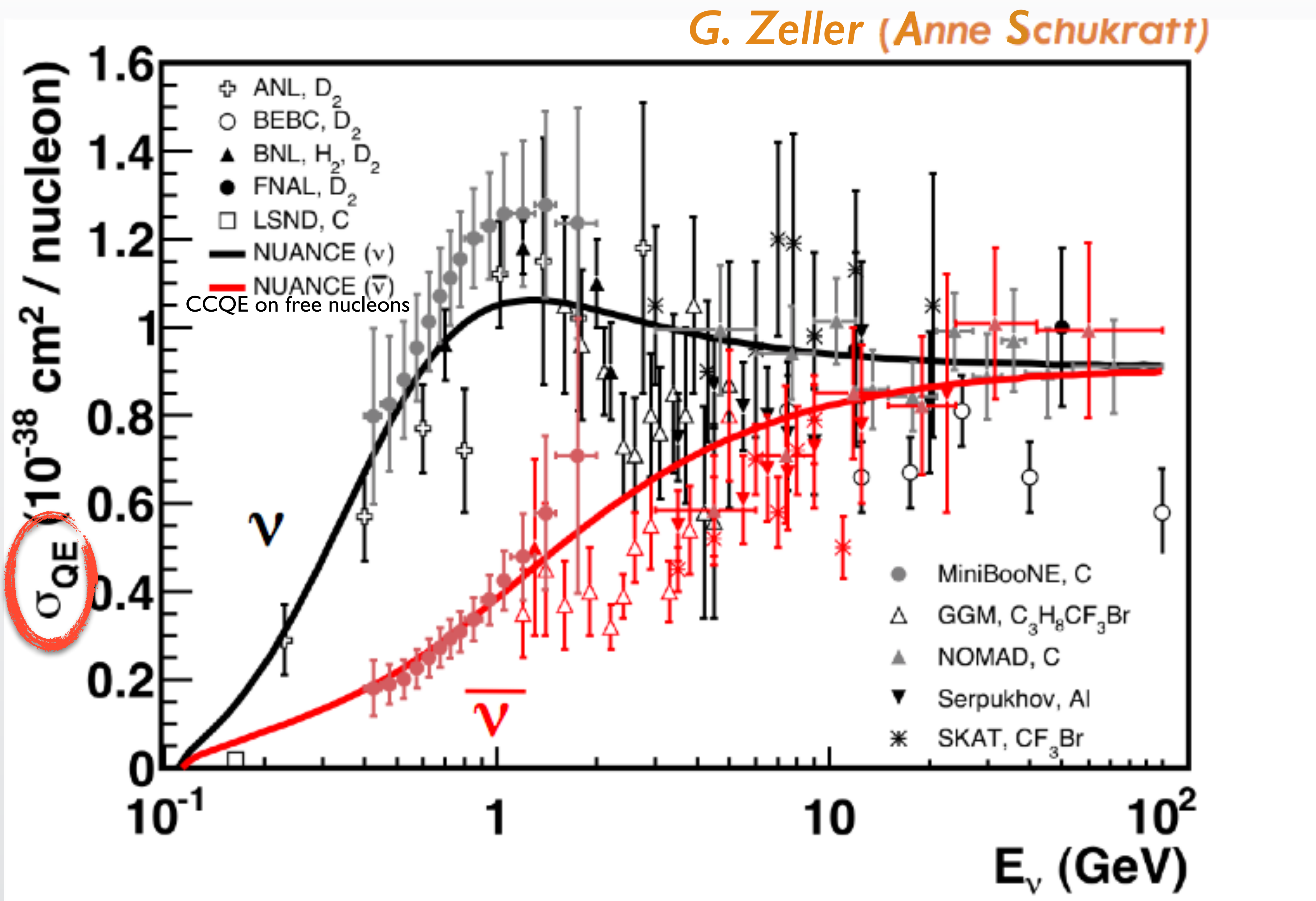
ArgoNeuT Coll. is grateful to Olga Lalakulich and Ulrich Mosel for providing the GiBUU predictions and for many useful discussions

anti-ν_μ CC 0 pion cross section as a function of the **reconstructed*** neutrino energy



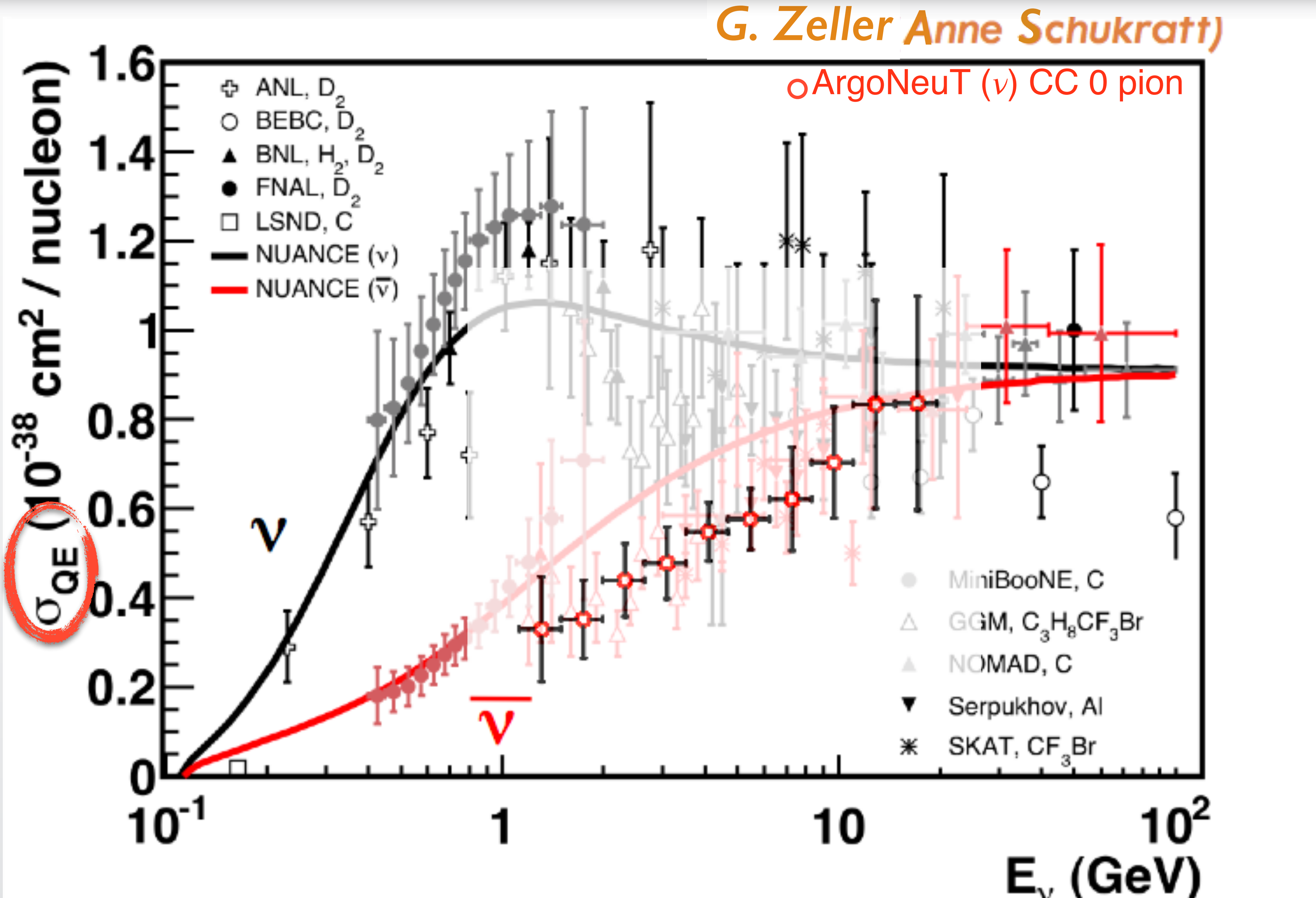
* from ***lepton AND proton reconstructed kinematics:*** $E_\nu = (E_\mu + \sum T_{pi} + T_X + E_{miss})$

T_X=recoil energy of the residual nuclear system [estimated from missing transverse momentum],
E_{miss}=missing energy [nucleon separation energy from Ar nucleus + excitation energy of residual nucleus (estimated by fixed average value)]

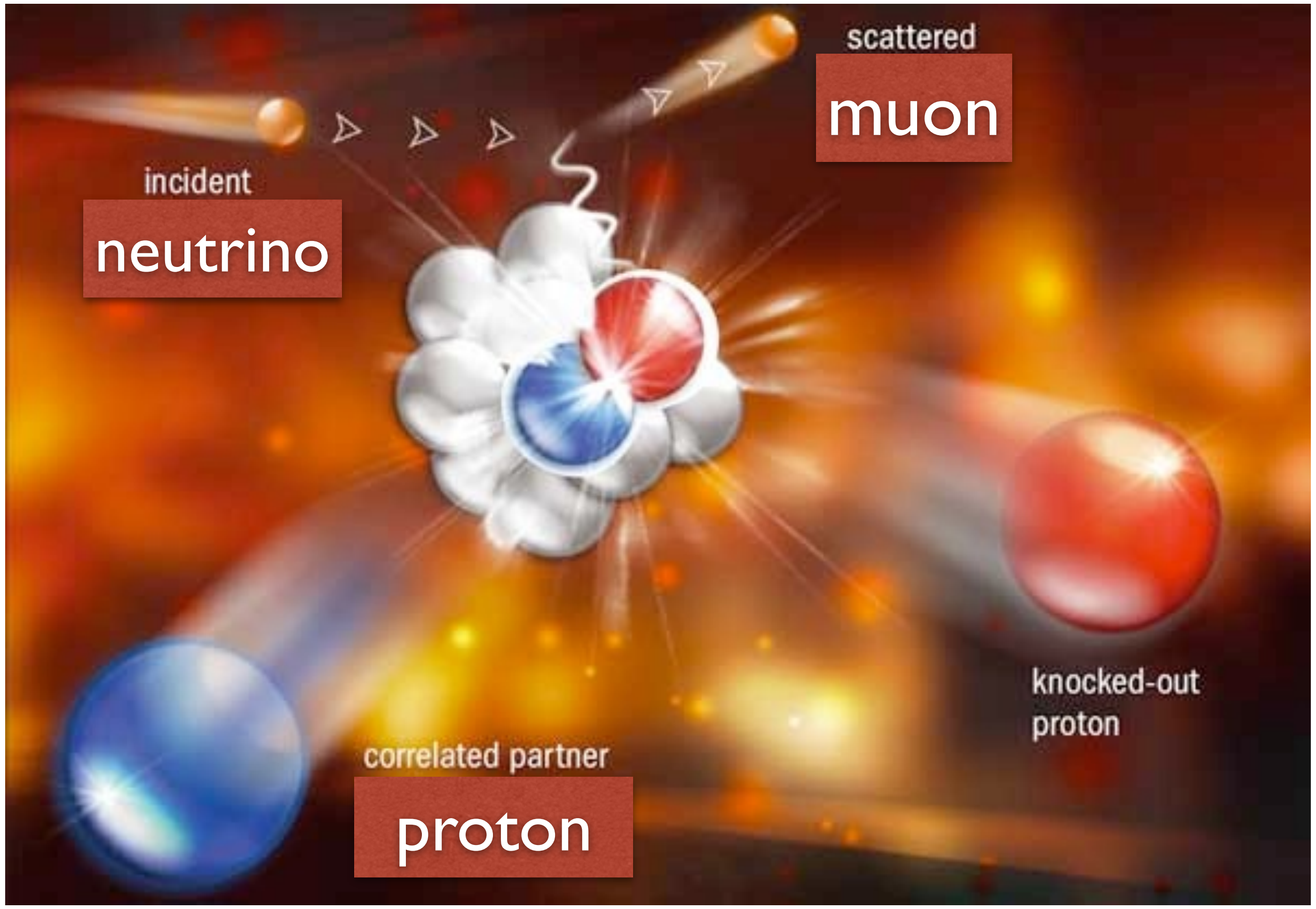


G. Zeller (Anne Schukraft)
ANL, D2
BEBC, D2
BNL, H2, D2
FNAL, D2
LSND, C
NUANCE (ν)
NUANCE (ν̄)
CCQE on free nucleons
MiniBooNE, C
GGM, C3H8CF3Br
NOMAD, C
Serpukhov, Al
SKAT, CF3Br
σQE (10^-38 cm² / nucleon)
Eν (GeV)
ν
ν̄

anti-ν_μ CC 0 pion cross section as a function of the **reconstructed*** neutrino energy



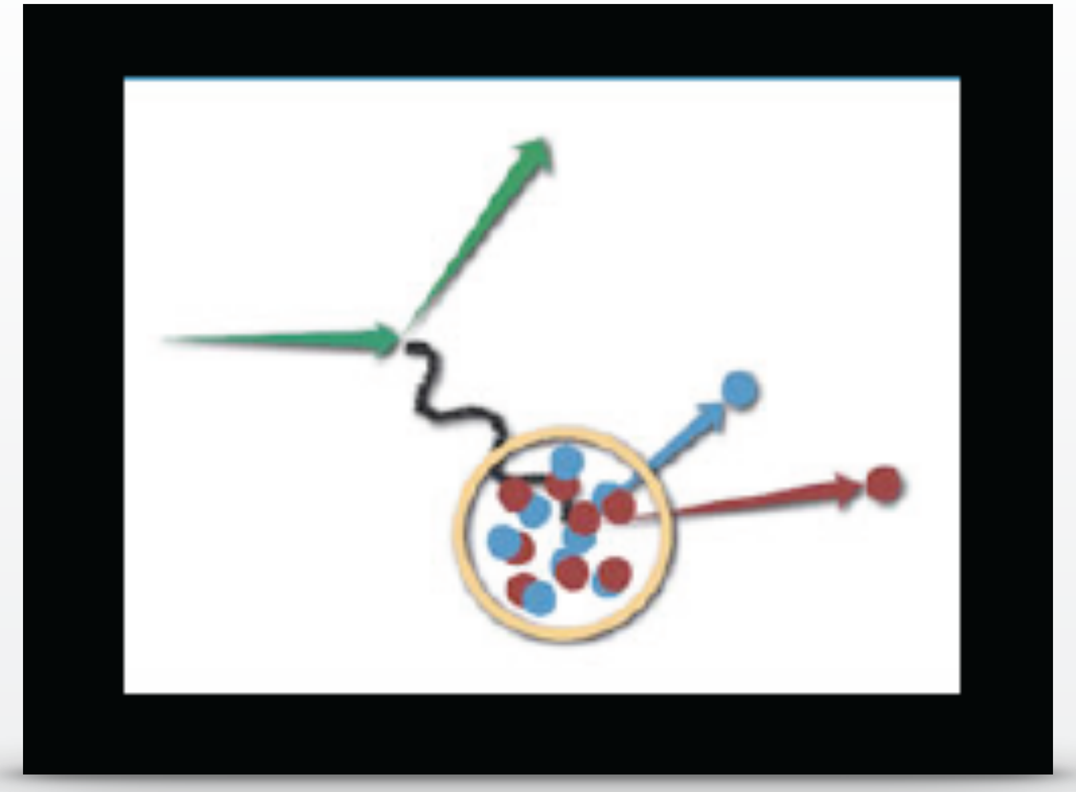
Note:
comparison of ArgoNeuT *CC-0 pion* data with CCQE experimental data and CCQE NUANCE predictions is reported just as guidance



Short Range Correlations

Nuclear effects

- Nuclear effects in (heavy) nuclear targets [initial state short-range nucleon-nucleon correlations **(NN SRC)**, meson-exchange currents **(MEC and IC)** and final state interactions **(FSI)** - ***and interference between the amplitudes of these mechanisms***] play a big role in scattering processes



e-scattering experiments accumulated decades of in-depth experience and detailed knowledge: to be transmitted to the ν-scattering sector

- The realization of consistent models including all these nuclear effect is now being actively pursued as well as their implementation in ν MonteCarlo generators

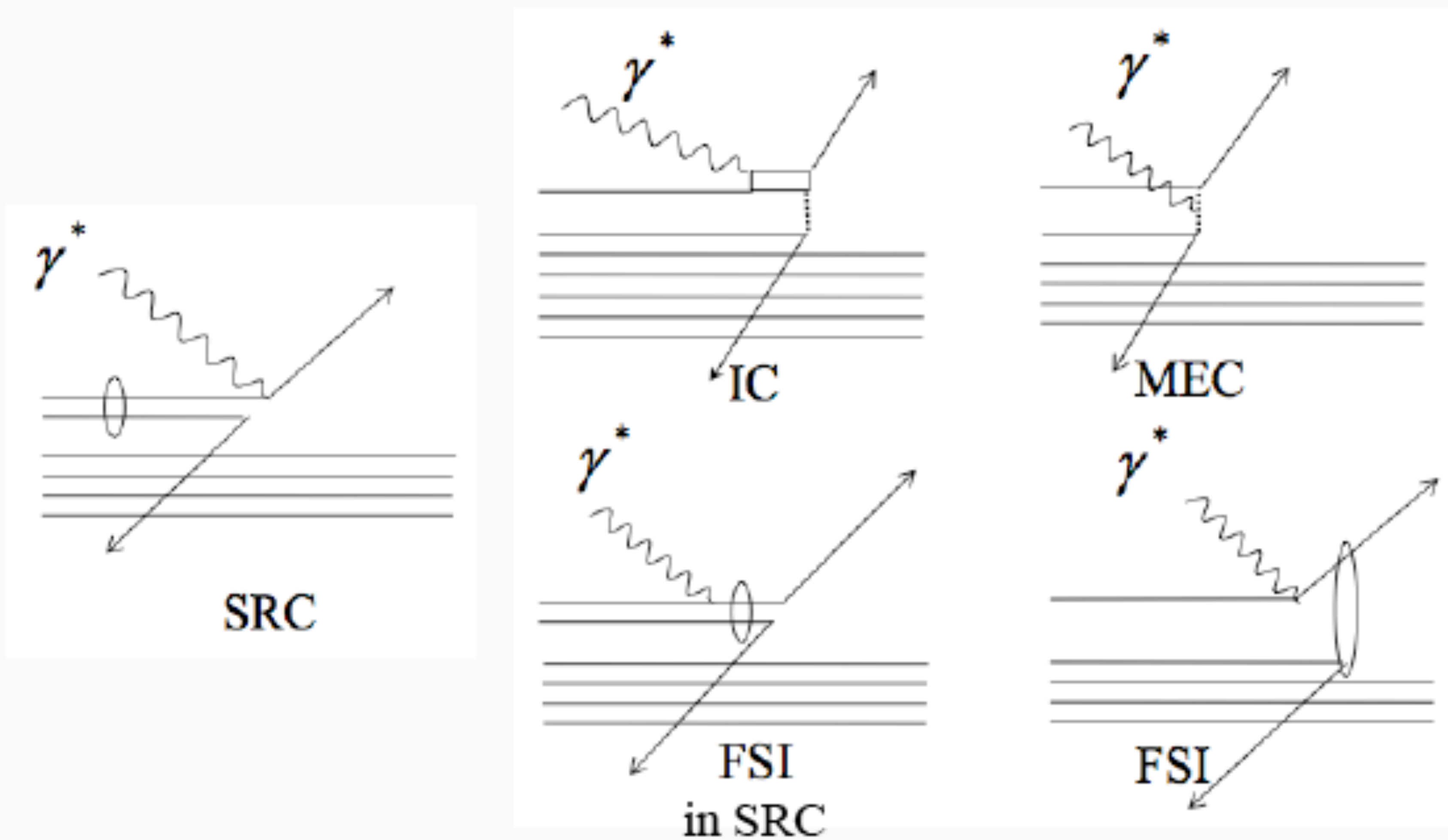
- The Time Projection Chamber (LArTPC) technique opens new perspectives for detailed reconstruction of final state event topologies from neutrino-nucleus interactions.

learning from e-scattering experiments

What are correlations?

Average Two-Nucleon Properties in the Nuclear Ground State

Two-body currents are not Correlations
(but add coherently)



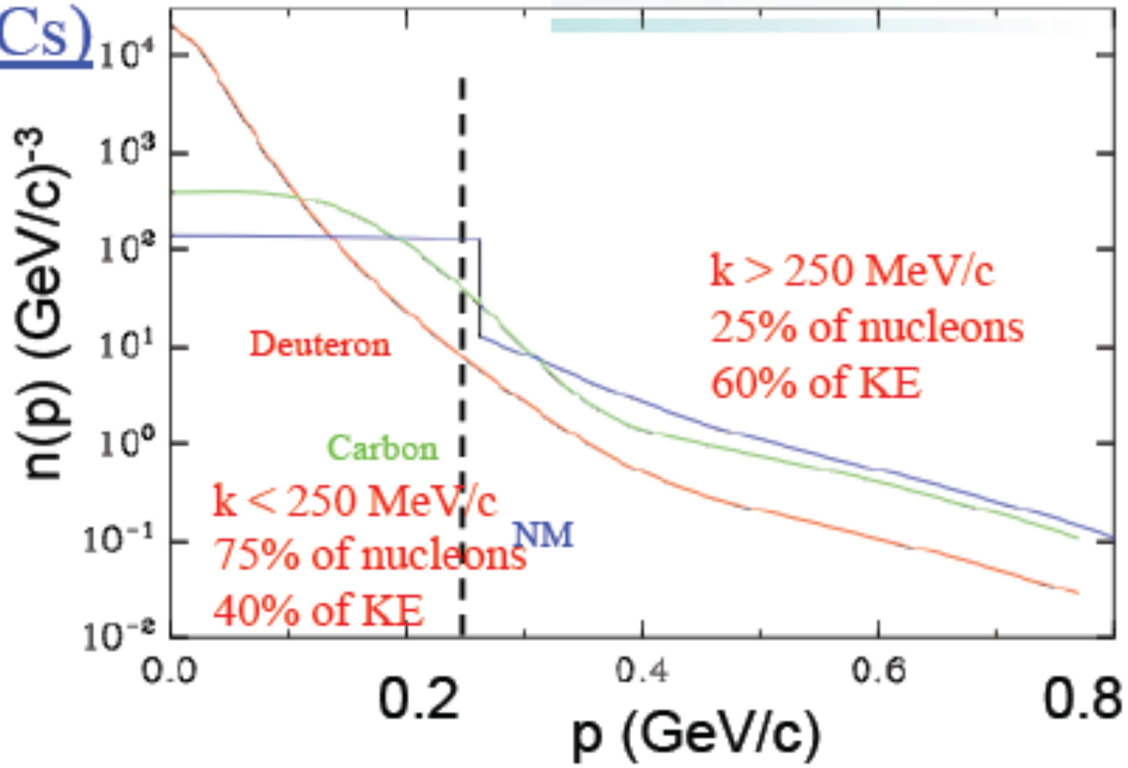
shown at NuINT'14 by L. Weinstein

NN SRC: learning from e-scattering experiments

Short Range Correlations (SRCs)

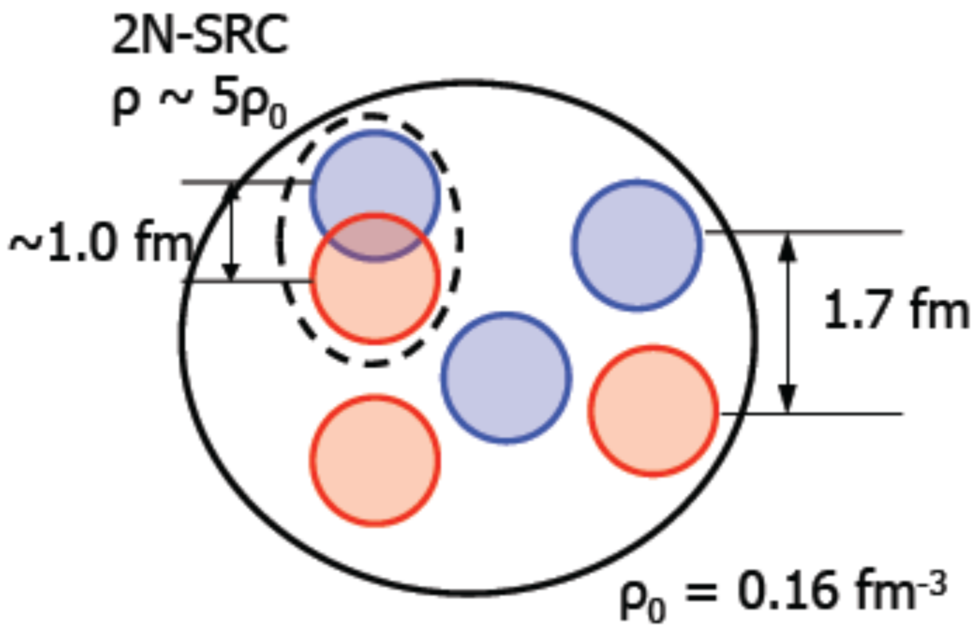
➔High momentum tails: $k > k_F$

Calculable for $A \leq 12$ nuclei and nuclear matter.
Not well constrained at $k >> k_f$



Effects:

- High momentum part of the nuclear wave function
- Short distance behavior of nucleons - modification??
- Cold dense nuclear matter
- Neutron Stars



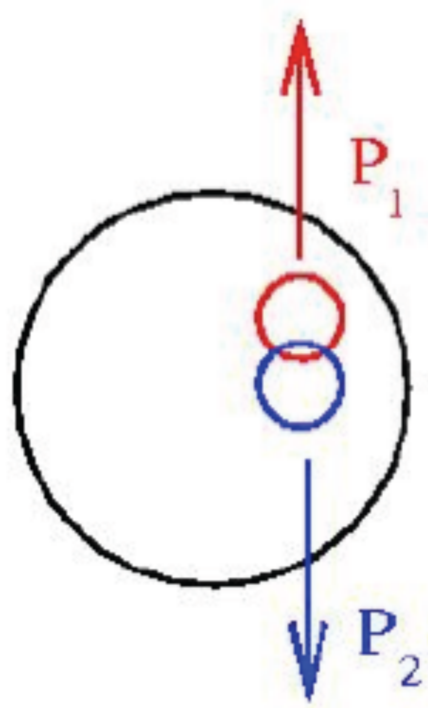
Nucleons are like people …

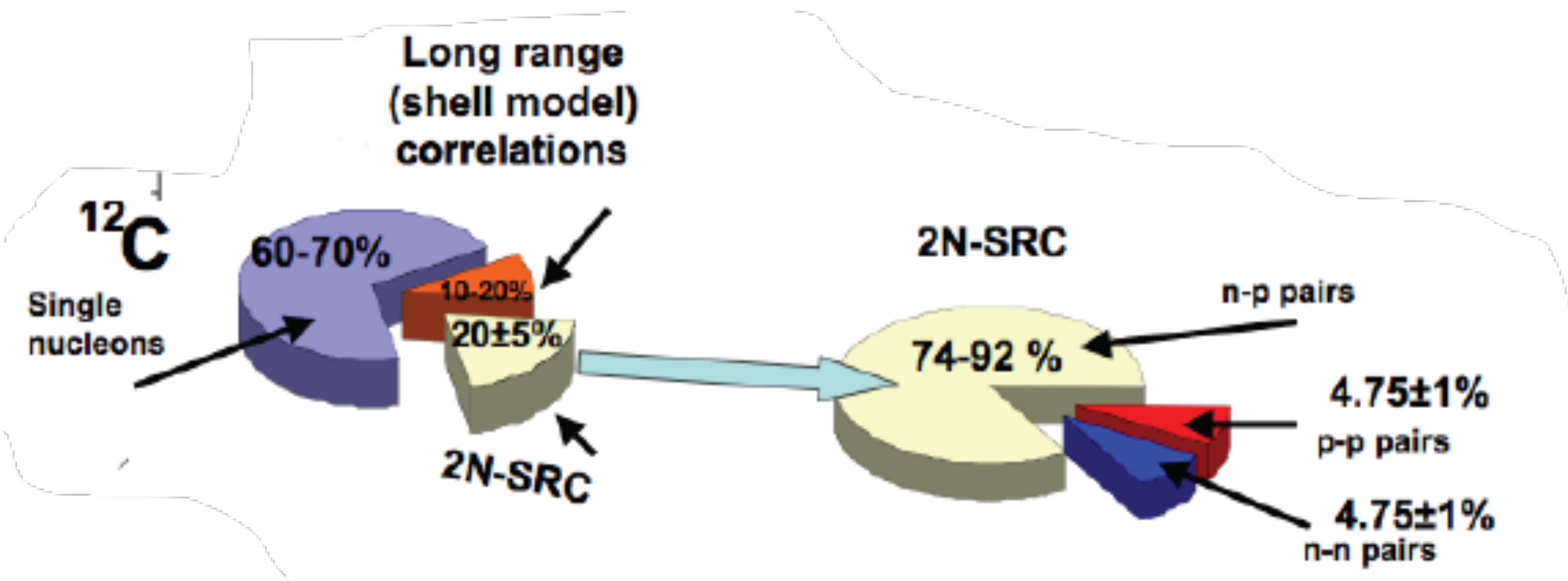
shown at NuINT'14 by L. Weinstein

Signatures for Correlations

An Experimentalist's Definition:

- A high momentum nucleon whose momentum is balanced by **one** other nucleon
  - NN Pair with
    - Large Relative Momentum
    - Small Total Momentum

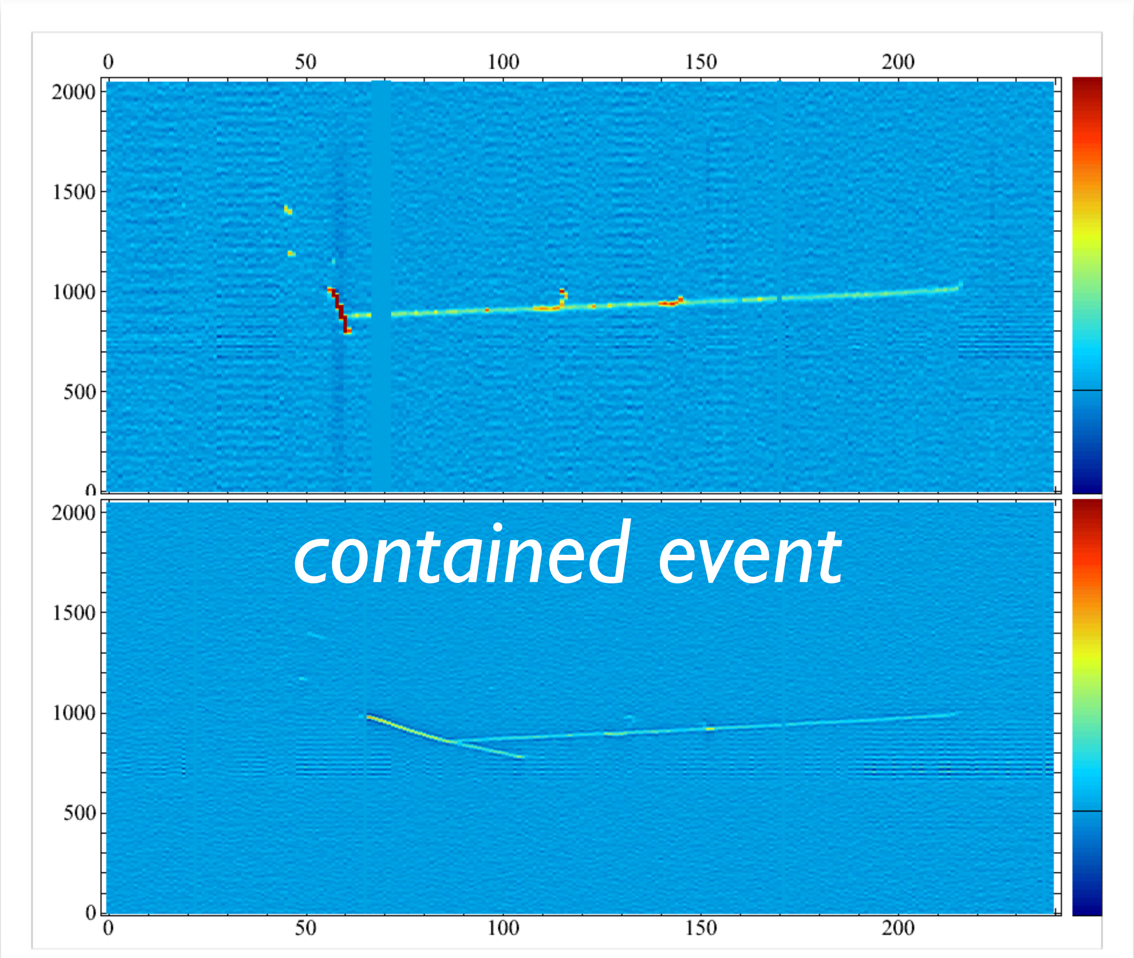


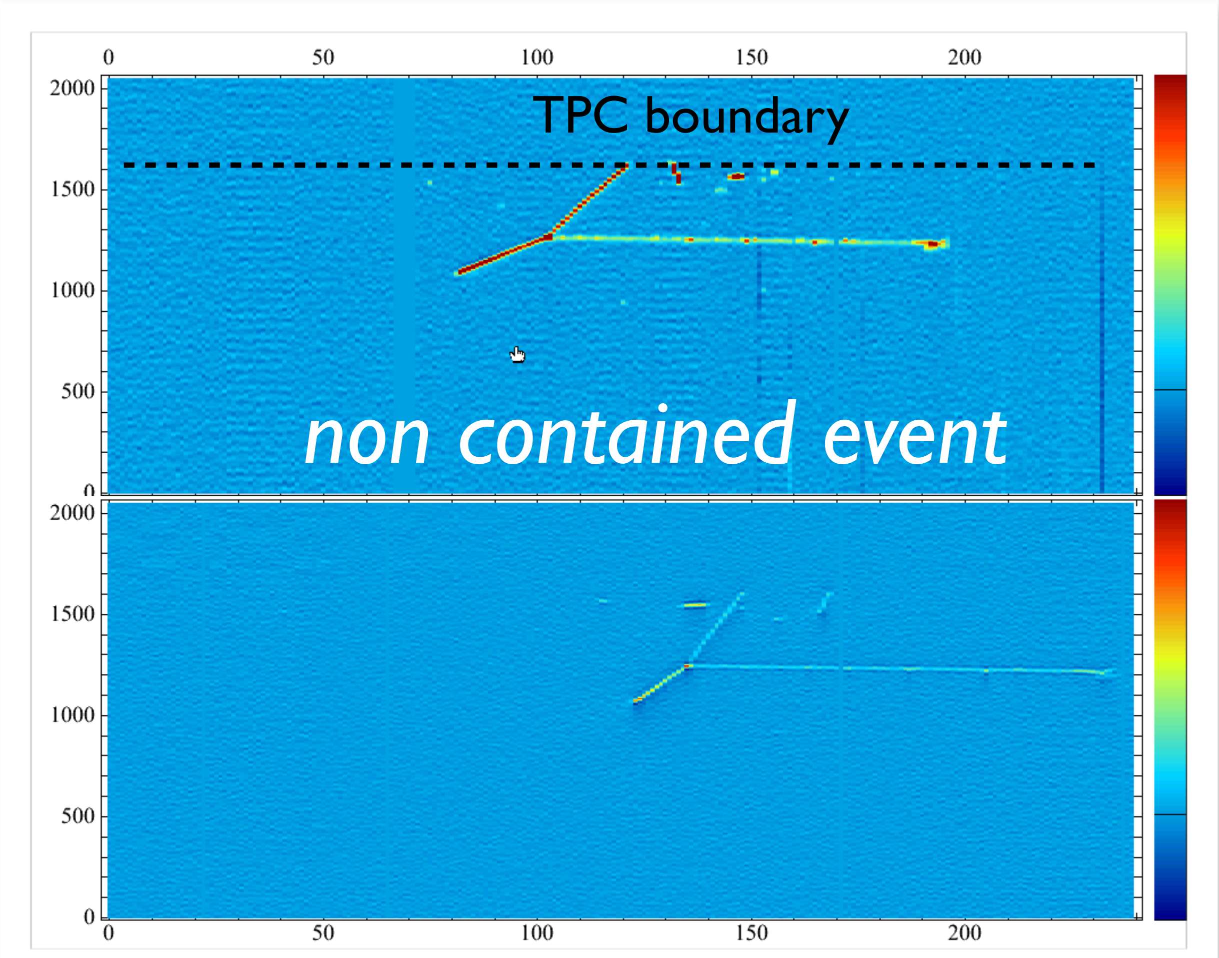


ArgoNeuT: detection of 2N knock-out events from *neutrino interactions*

Data sample: N=2 protons in final state, i.e. (μ^- + 2p) triple coincidence topology - ***30 events*** (*19 collected in the anti-neutrino mode run* and *11 in the neutrino mode run*) with the leading negative muon accompanied by a pair of protons at the interaction vertex

Both proton tracks are required to be fully contained inside the fiducial volume of the TPC and above energy threshold.
From detector simulation, acceptance for the (μ^-+2p) sample is estimated to be around 35% (dominated by the containment requirement in FV).





(μ^-+2p) data sample

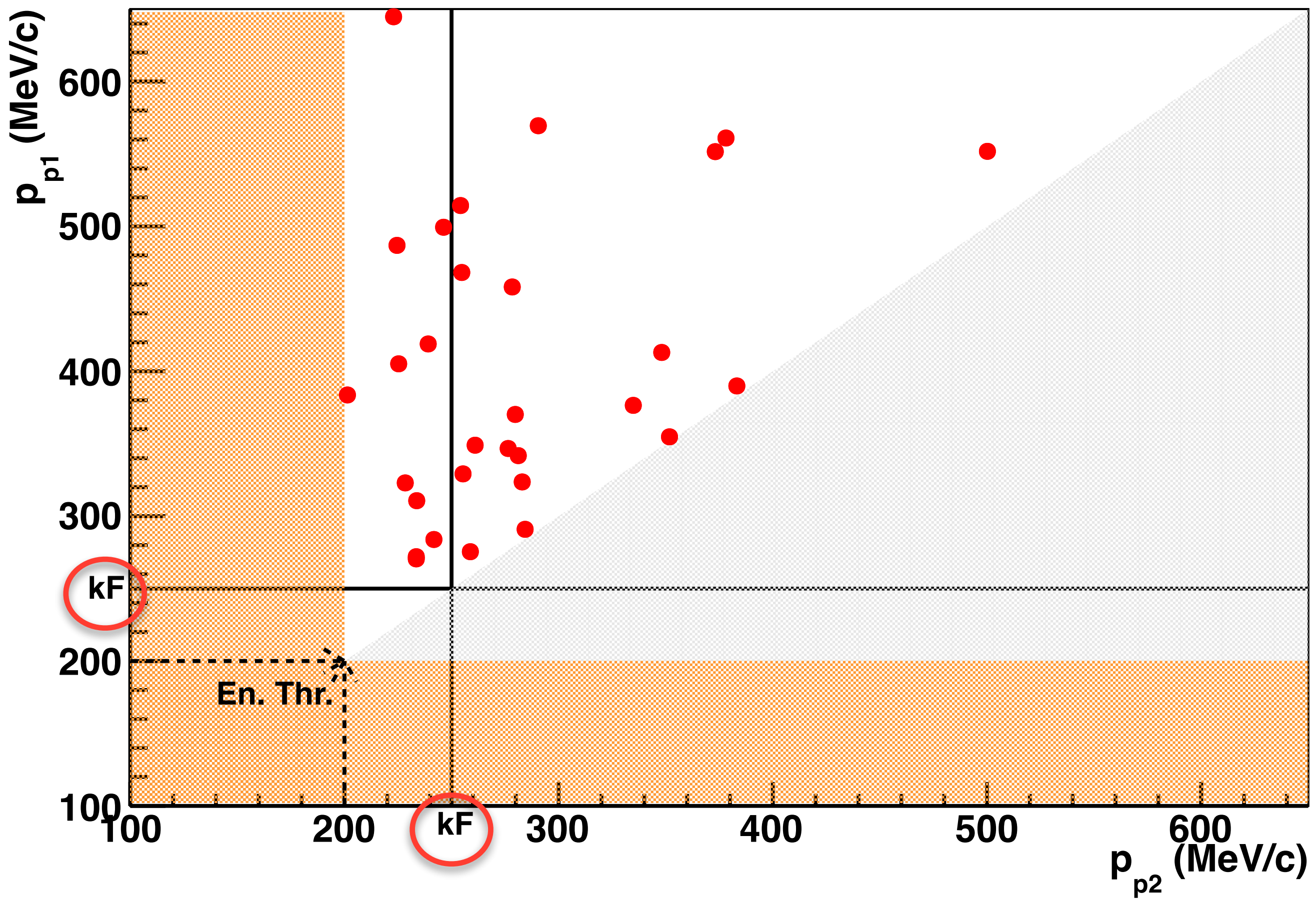
- Fully reconstructed events. Measured quantities*:
  - the 3-momentum of the muon, determined from the matched track in ArgoNeuT and MINOS-ND,
  - the sign of the muon provided by MINOS-ND, and
  - the energy and direction of propagation of the two protons measured by ArgoNeuT.

- Event ratios:
  (μ^-+2p)/(μ^-+Np)=21% (26%) and
  (μ^-+2p)/CC-inclusive~2% (~4%)
  for the anti-neutrino-mode run (neutrino-mode) [efficiency corrected]

- According to GENIE MC simulation: ~40% of (μ^-+2p) are due to CC QE interactions and about 40% to CC RES pionless interactions.

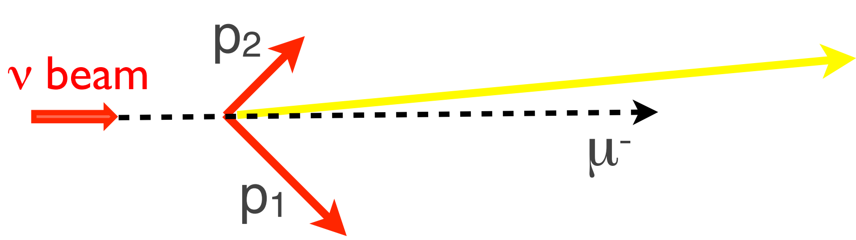
**muon momentum resolution 5-10% from MINOS-ND*
proton angular resolution: 1-1.5^0 , depending on track length
proton energy resolution: ~6% for protons above Fermi momentum

(μ^-+2p) data sample



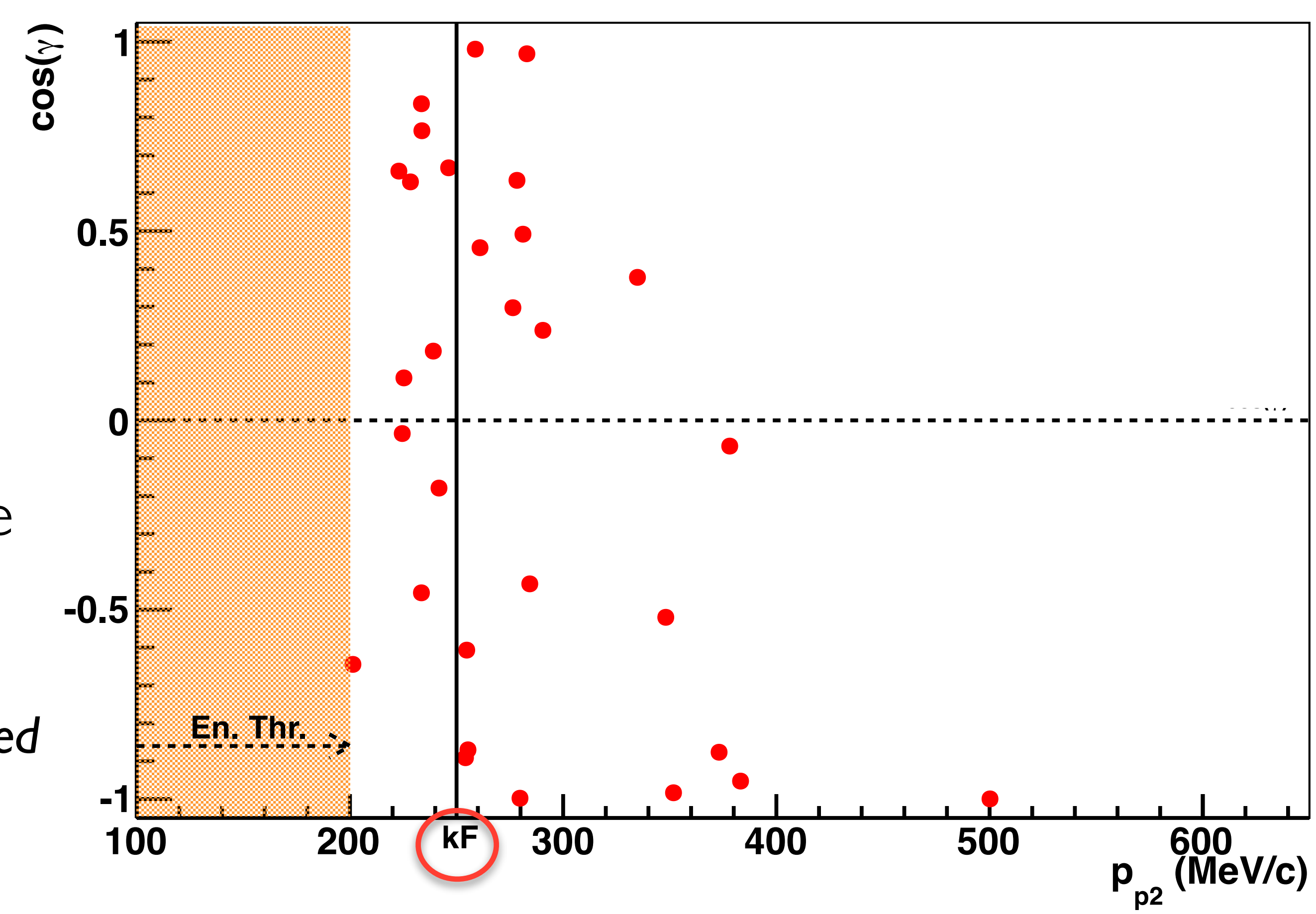
Momentum of the more energetic proton $\mathbf{p_{p1}}$ in the pair vs. momentum of the other (less energetic) proton $\mathbf{p_{p2}}$

Most of the events (19 out of 30) have both protons above Fermi momentum of the Ar nucleus ($k_F \simeq 250$ MeV)



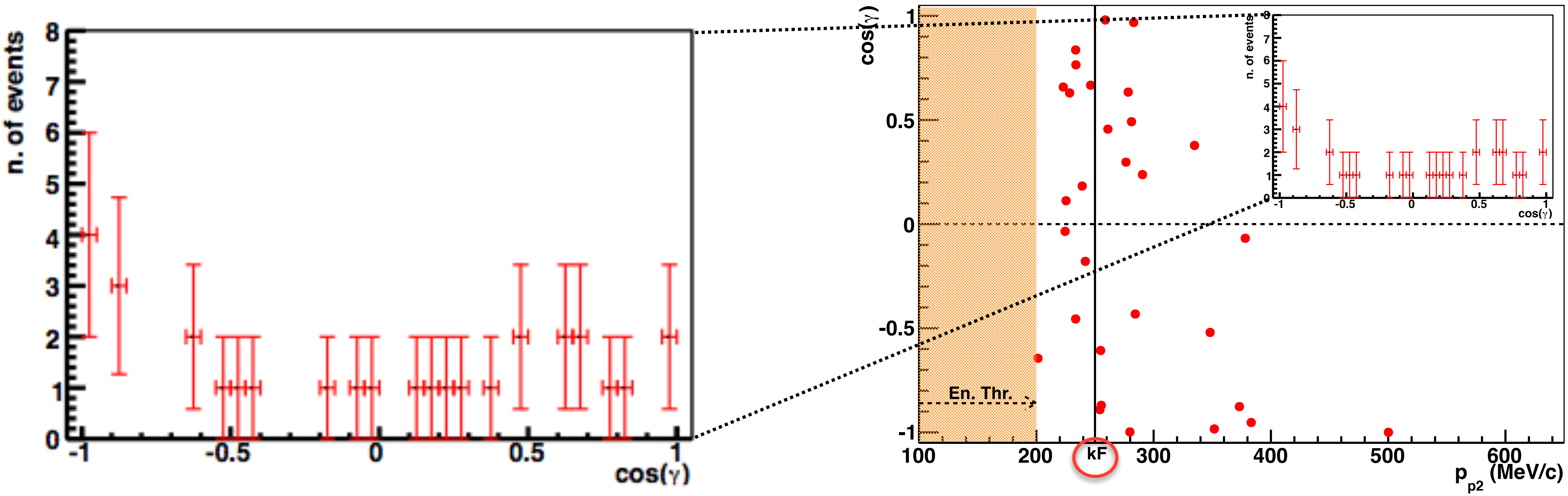
cos(γ) vs momentum of the least energetic proton $\mathbf{p_{p2}}$ in the pair for the 19 events with $\mathbf{p_{p1}, p_{p2} \geq k_F}$

*γ=angle in space between the two detected proton tracks in the **Lab reference frame***



(μ^-+2p) data sample - ***back-to-b protons in the Lab***

cos(γ) vs momentum of the least energetic proton p_{p2} in the pair

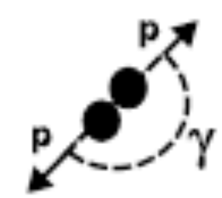


Four of the 19 2p-events are found with the pair in a **back-to-back** configuration in the Lab frame cos(γ)<-0.95

In all four events one proton is almost exactly balanced by the other

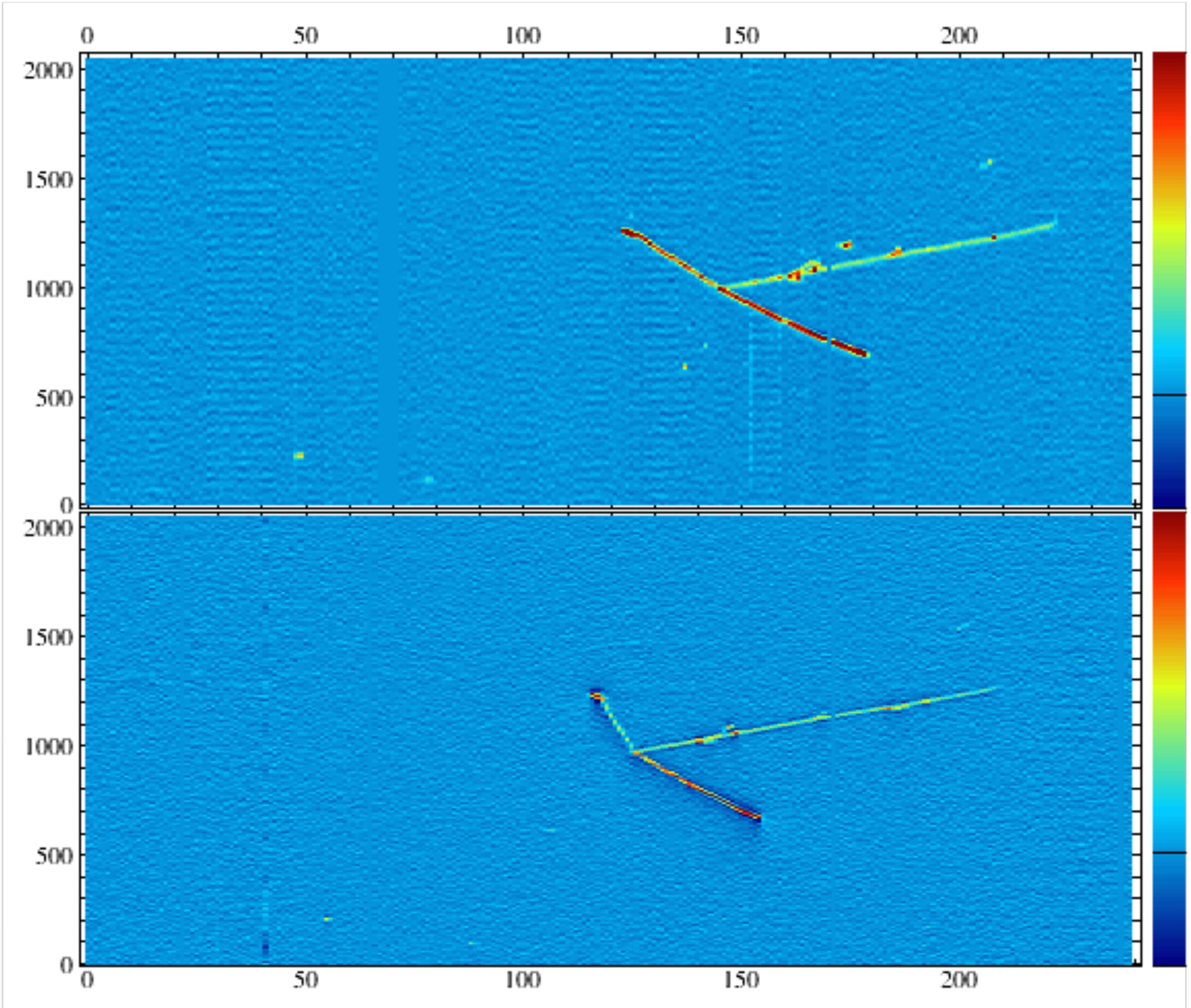
$p_{p1}, p_{p2} \geq k_F$ and $\vec{p}_{p1} \simeq -\vec{p}_{p2}$

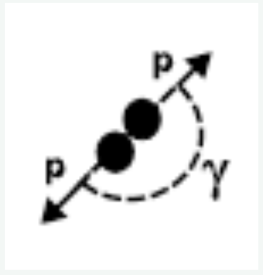
“Hammer Events”



$(\mu^{-}+2p)$ data sample - ***4 "Hammer Events"***

Visually the signature of these events gives the appearance of a hammer, with the muon forming the handle and the back-to-back protons forming the head.

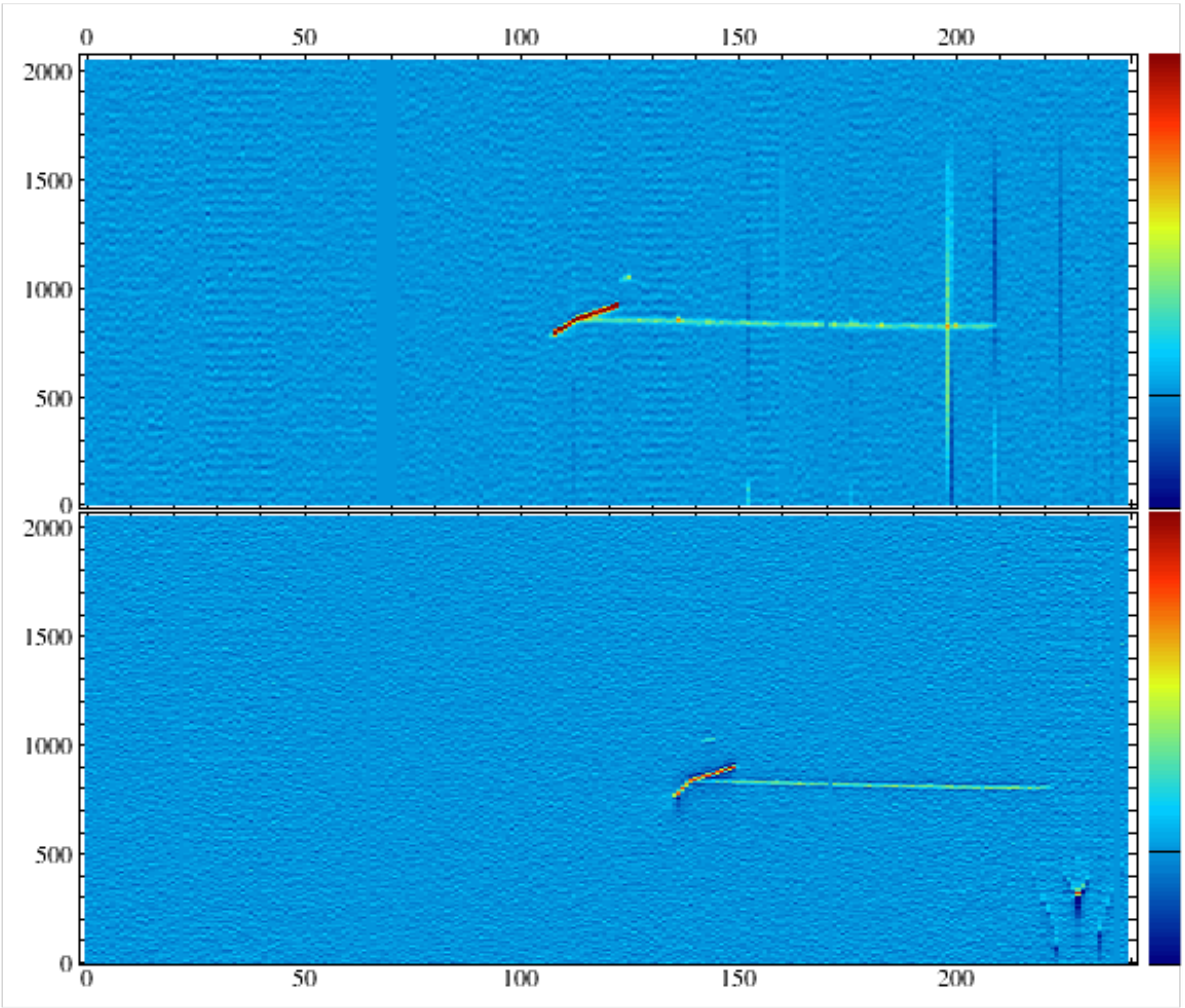


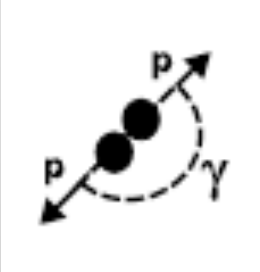


$\cos(\gamma)<-0.95$

(μ^-+2p) data sample - ***4 "Hammer Events"***

Visually the signature of these events gives the appearance of a hammer, with the muon forming the handle and the back-to-back protons forming the head.





cos(γ)<-0.95

(μ⁻+2p) data sample - ***4 “Hammer Events”***

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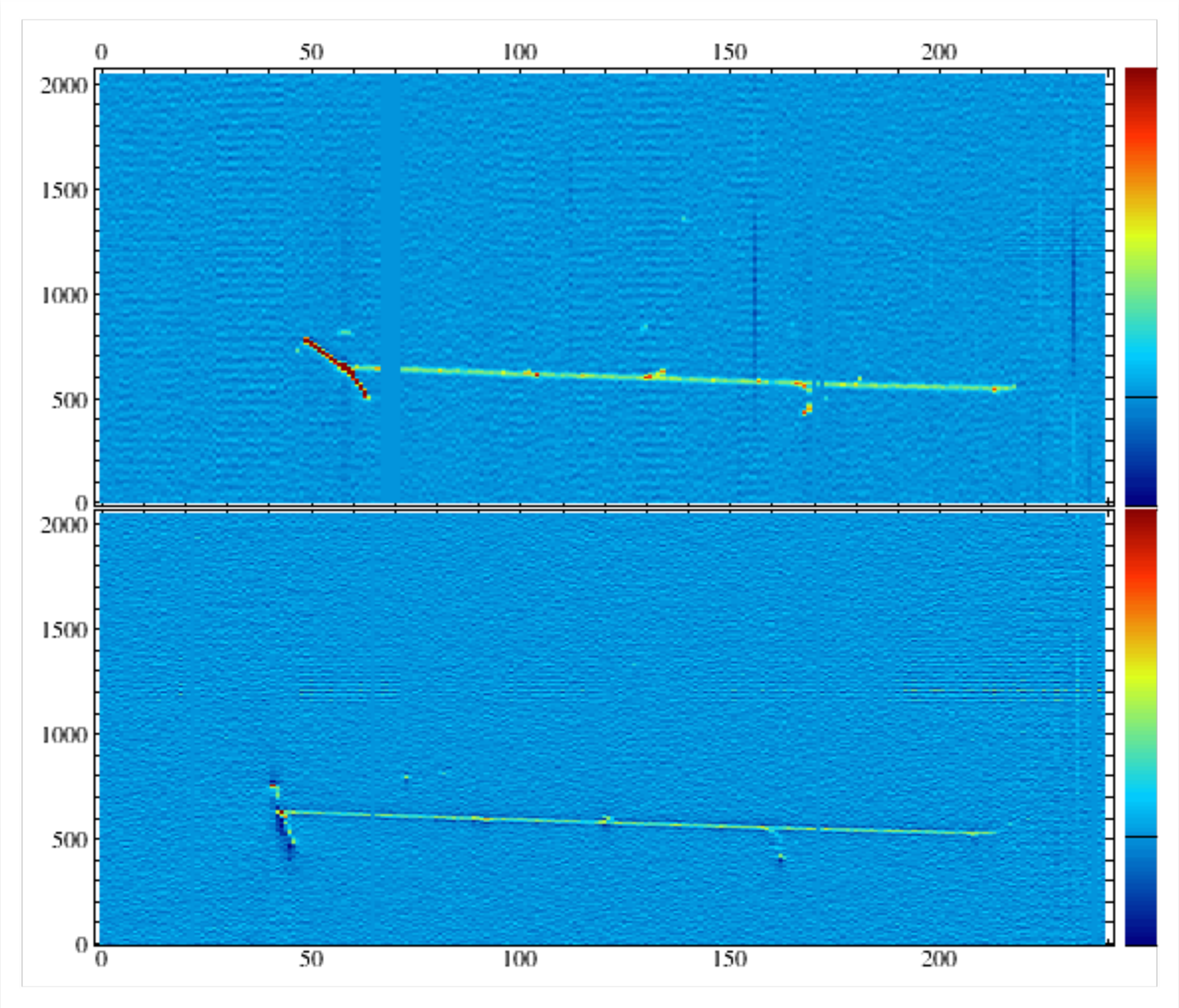
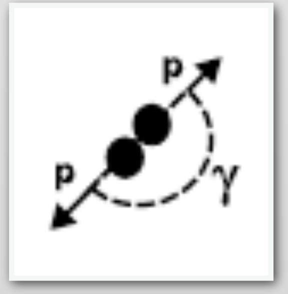
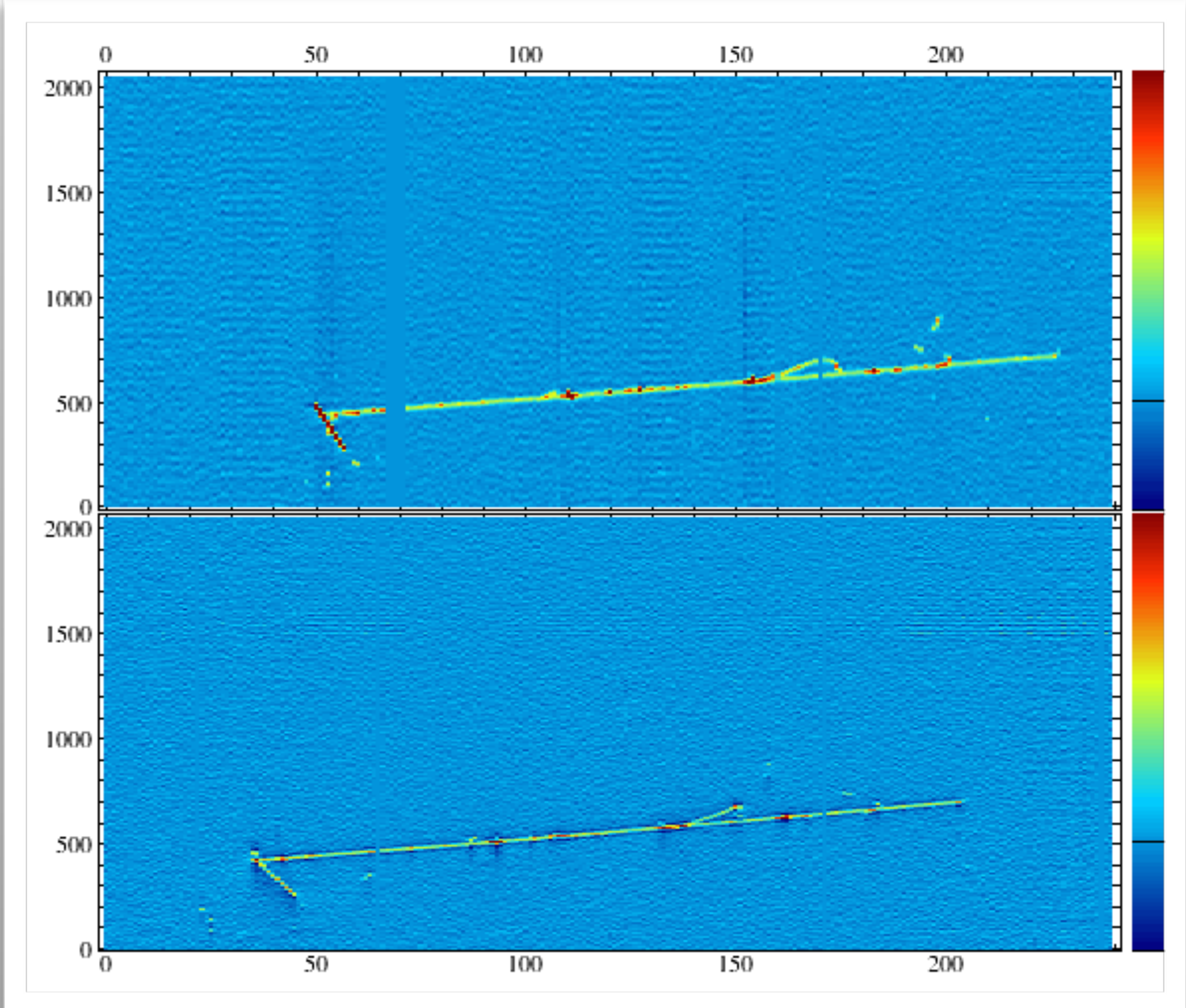


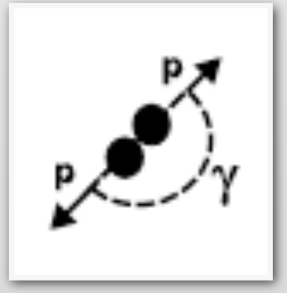


$\cos(\gamma) < -0.95$

(μ^-+2p) data sample - **4 *“Hammer Events”***

Visually the signature of these events gives the appearance of a hammer, with the muon forming the handle and the back-to-back protons forming the head.





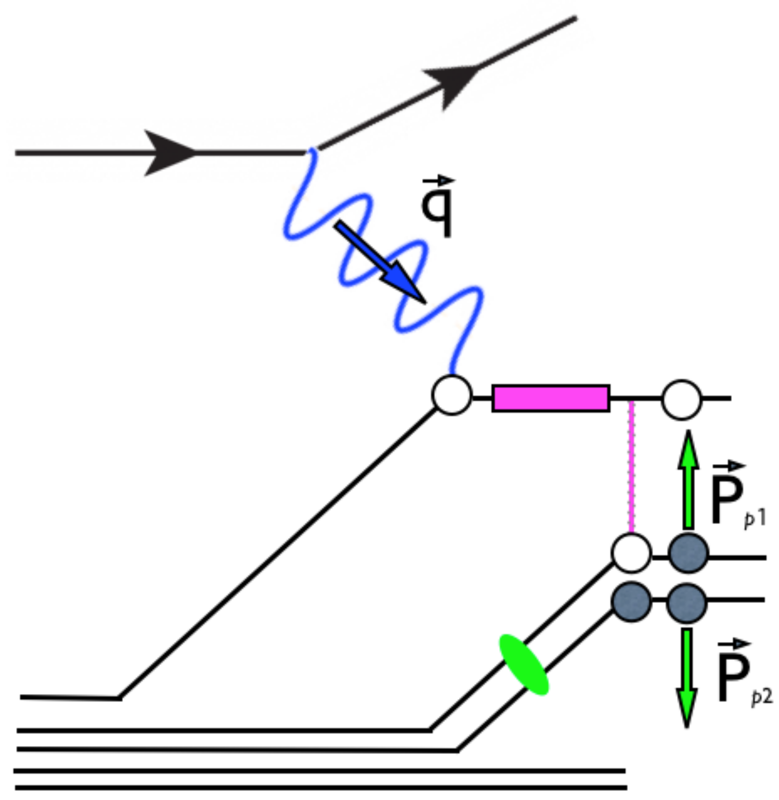
cos(γ)<-0.95

2-p knock-out CC reactions involving SRC pairs(I)

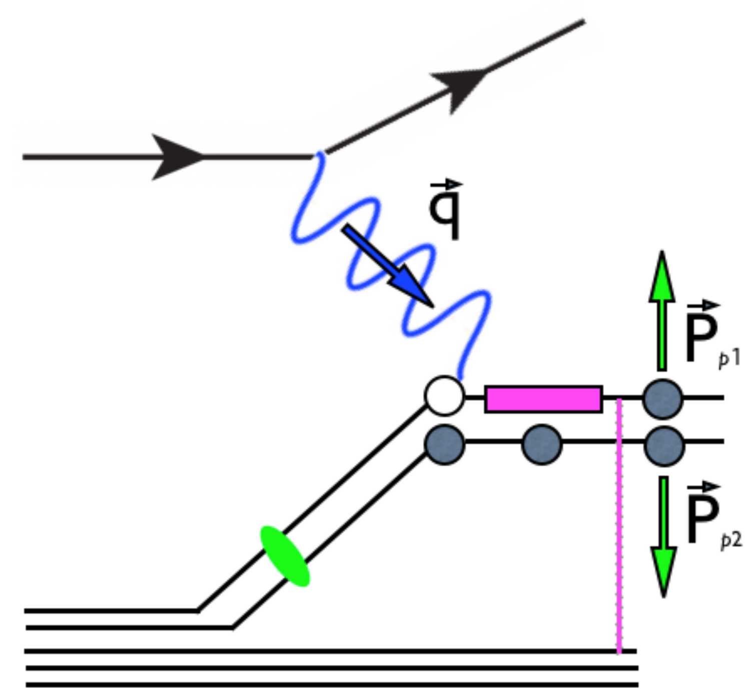
I) CC RES pionless mechanisms involving a pre-existing ***np*** pair in the nucleus.

Pictorial diagrams of examples of two-proton knock-out CC reactions involving *np* SRC pairs

- SRC (green symbol)
- nucleons in the target nucleus are denoted by open-full dots (n-p)
- wide solid lines (purple) represent RES nucleonic states
- (purple) lines indicate pions



via nucleon RES excitation and subsequent two-body absorption of the decay π^+ by a SRC pair



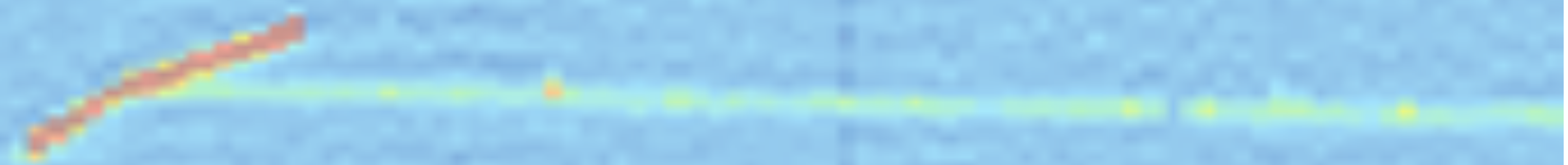
from RES formation inside a SRC pair (hit nucleon in the pair) and de-excitation through multi-body collision within the A-2 nuclear system

absorption is a two/multi-body reaction

large momentum transfer to nuclear system

Back-to-back proton pairs in the Lab frame

Back-to-back pp pairs in the Lab frame can be seen as "snapshots" of the initial pair configuration in the case of RES processes with no or low momentum transfer to the pair.



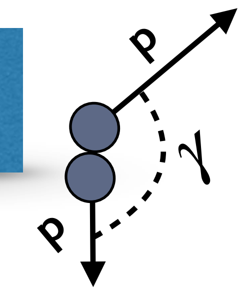
In all four "Hammer" events, both protons have:

- **momentum significantly above the Fermi momentum,**
- **with one almost exactly balanced by the other**
- **all events show a rather large missing transverse momentum,**

$$p^{T}_{miss} \geq 300\ MeV/c$$

These features **look compatible with the hypothesis of CC RES pionless reactions involving pre-existing SRC *np* pairs.**

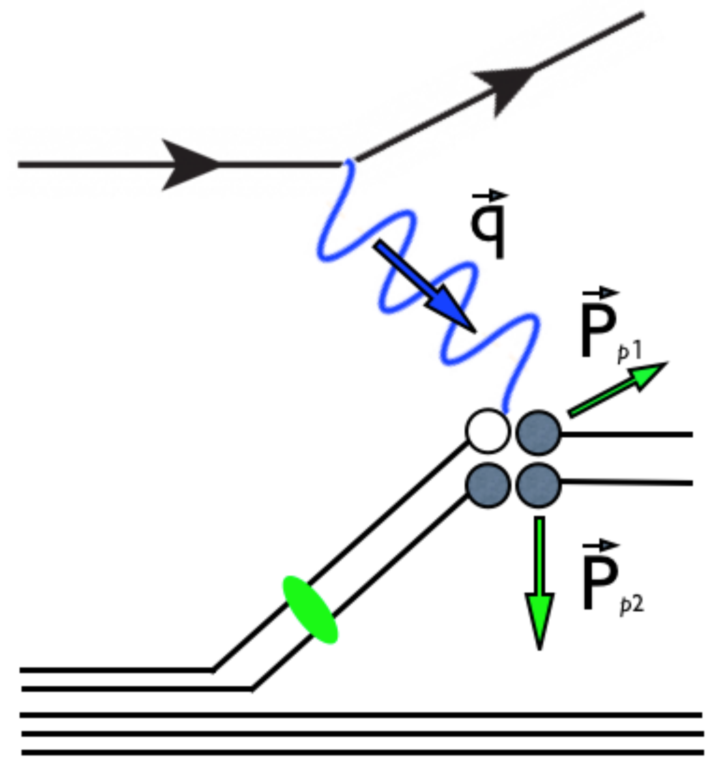
2-p knock-out CC reactions involving SRC pairs(II)



2) CC QE one-body neutrino reactions, through virtual charged weak boson exchange on the neutron of a SRC ***np*** pair

Pictorial diagrams of examples of two-proton knock-out CC reactions involving *np* SRC pairs

- SRC (green symbol)
- nucleons in the target nucleus are denoted by open-full dots (n-p)
- wide solid lines (purple) represent RES nucleonic states
- (purple) lines indicate pions



The high relative momentum will cause the correlated proton to recoil and be ejected.

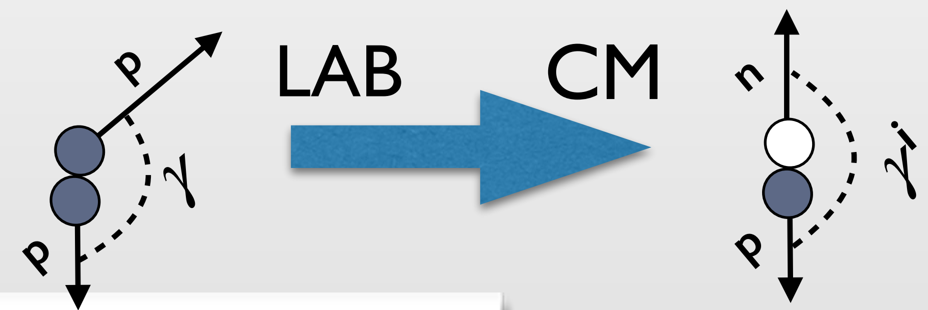
Within impulse approximation,

- the struck nucleon **p1** being the higher in momentum and
- the lower **p2** identified as the recoil spectator nucleon from within the SRC

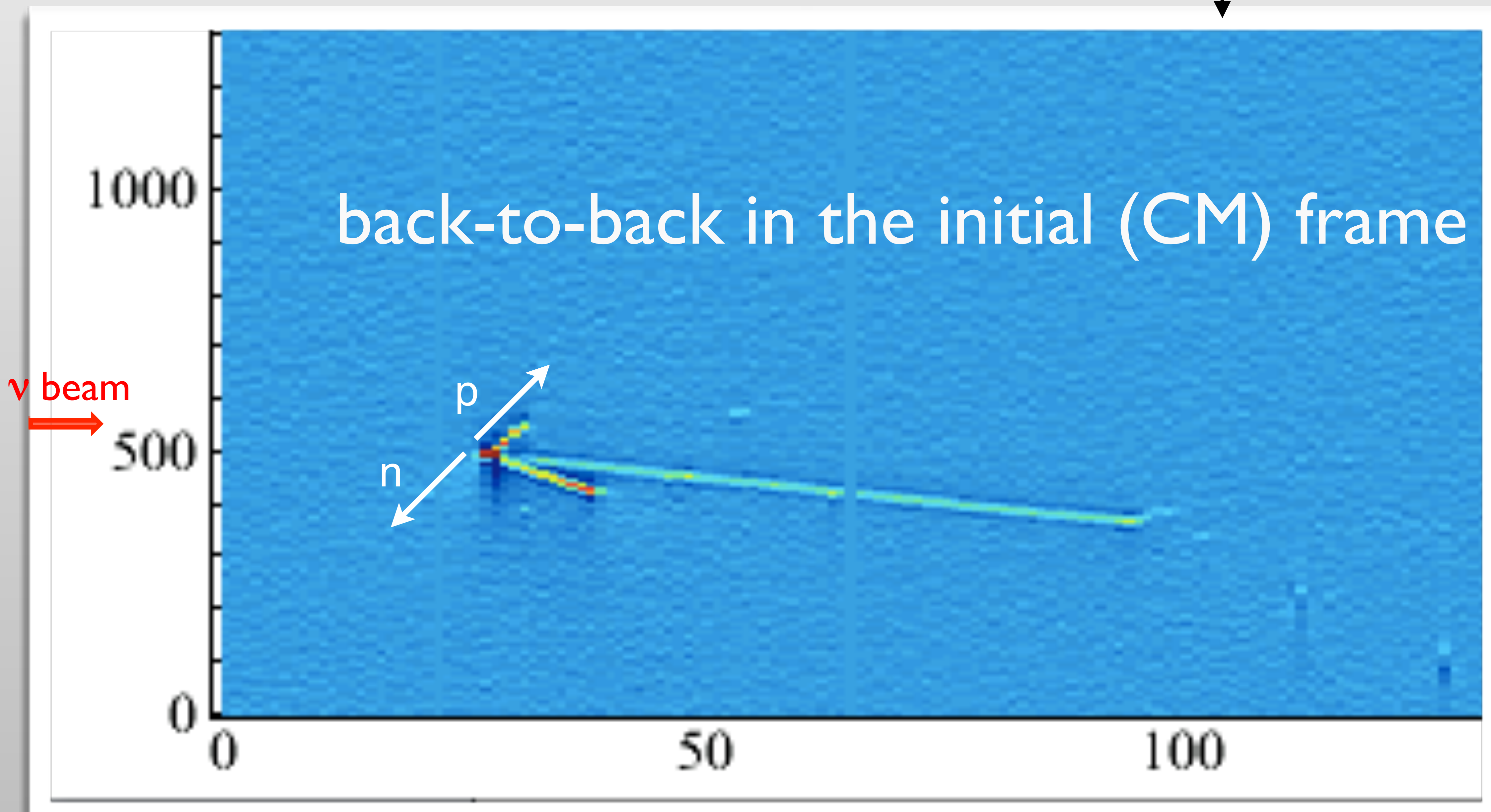
(μ^-+2p) - Initial momentum reconstruction

With an approach similar to the electron scattering triple coincidence analysis, the initial momentum of the struck neutron $\vec{p}_n{}^i$ is determined by transfer momentum vector subtraction to the higher proton momentum *[lower momentum p2 identified as recoil spectator nucleon from within SRC]*

$$\vec{p}_n{}^i = \vec{p}_{p1} - \vec{q} \quad \Leftrightarrow$$

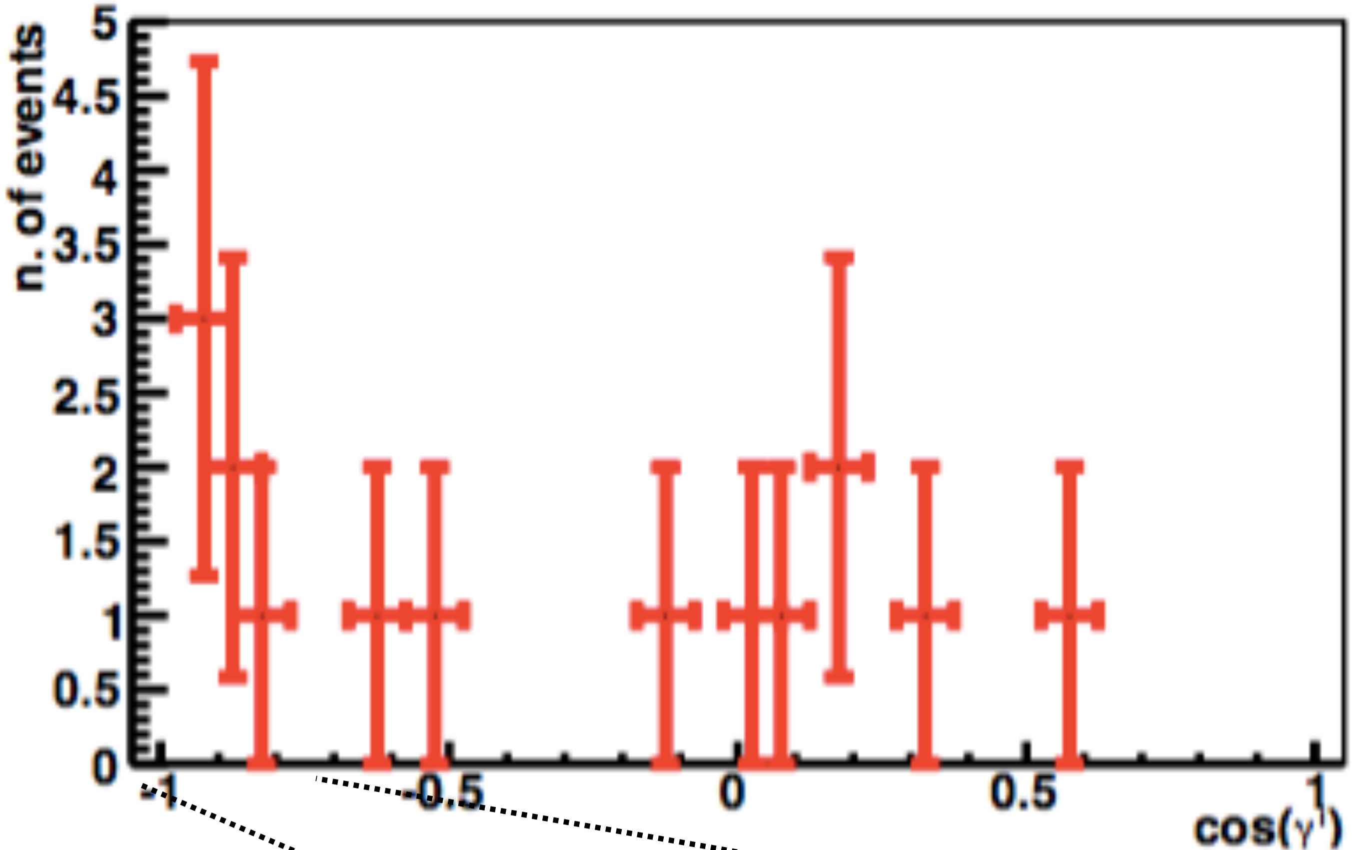


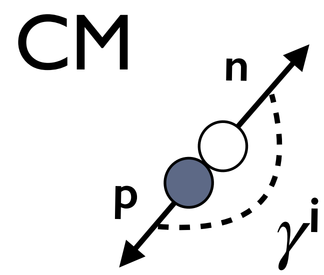
$\vec{q}$ is calculated from the reconstructed E_ν and the measured muon kinematics



(μ^-+2p) - Initial momentum reconstruction

In most cases the reconstructed initial momentum is found opposite to the direction of the recoil proton ($\cos(\gamma^i) < 0$)

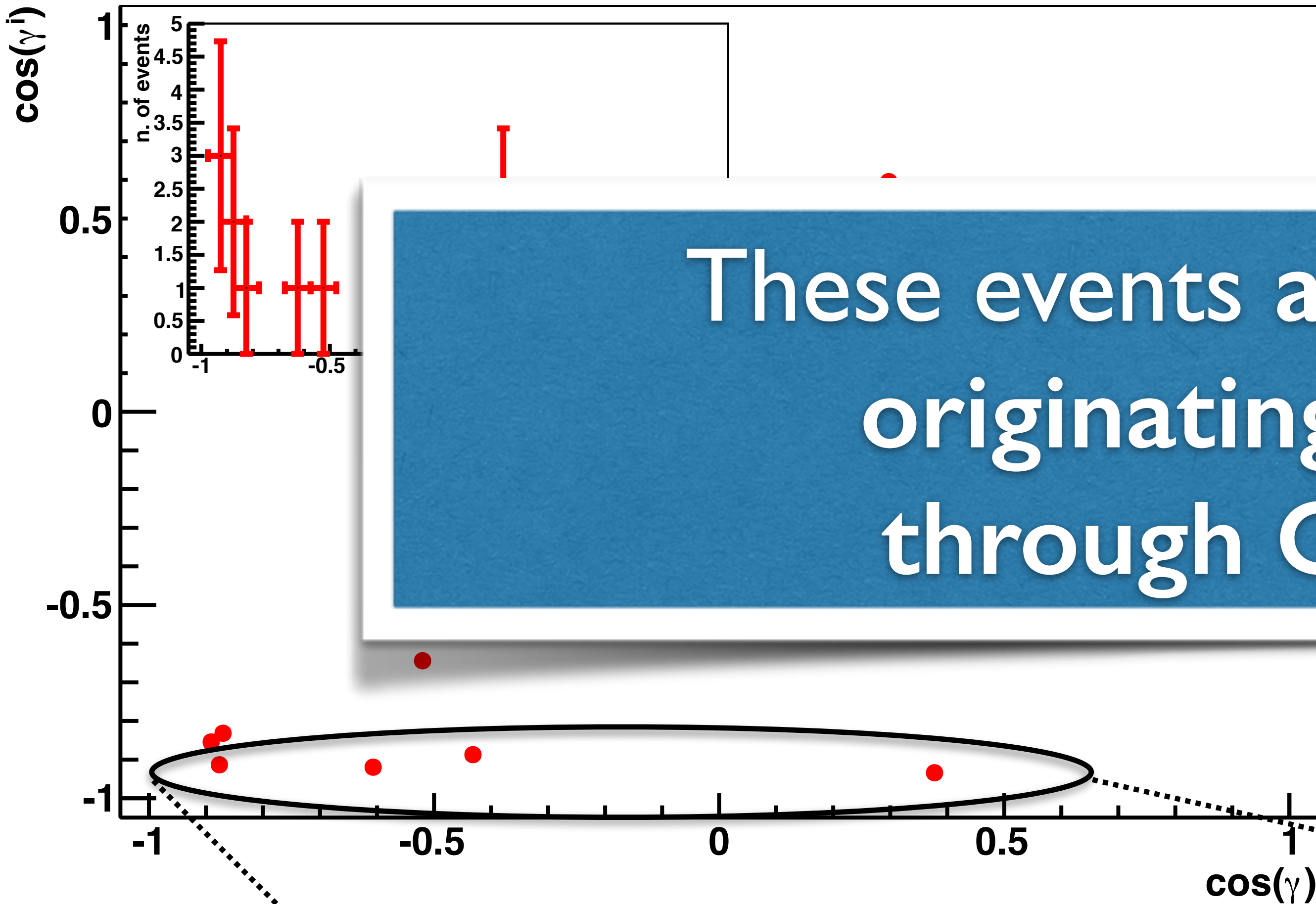




*γ^i=opening angle between the reconstructed struck nucleon and the recoil proton in the np **initial** pair*

A fraction of
the events exhibit a strong angular
correlation peaking at large,
back-to-back initial momenta

Back-to-back proton pairs in the initial state



cos(γ^i) vs cos(γ)

ted

np

detected proton tracks in the

Lab reference frame

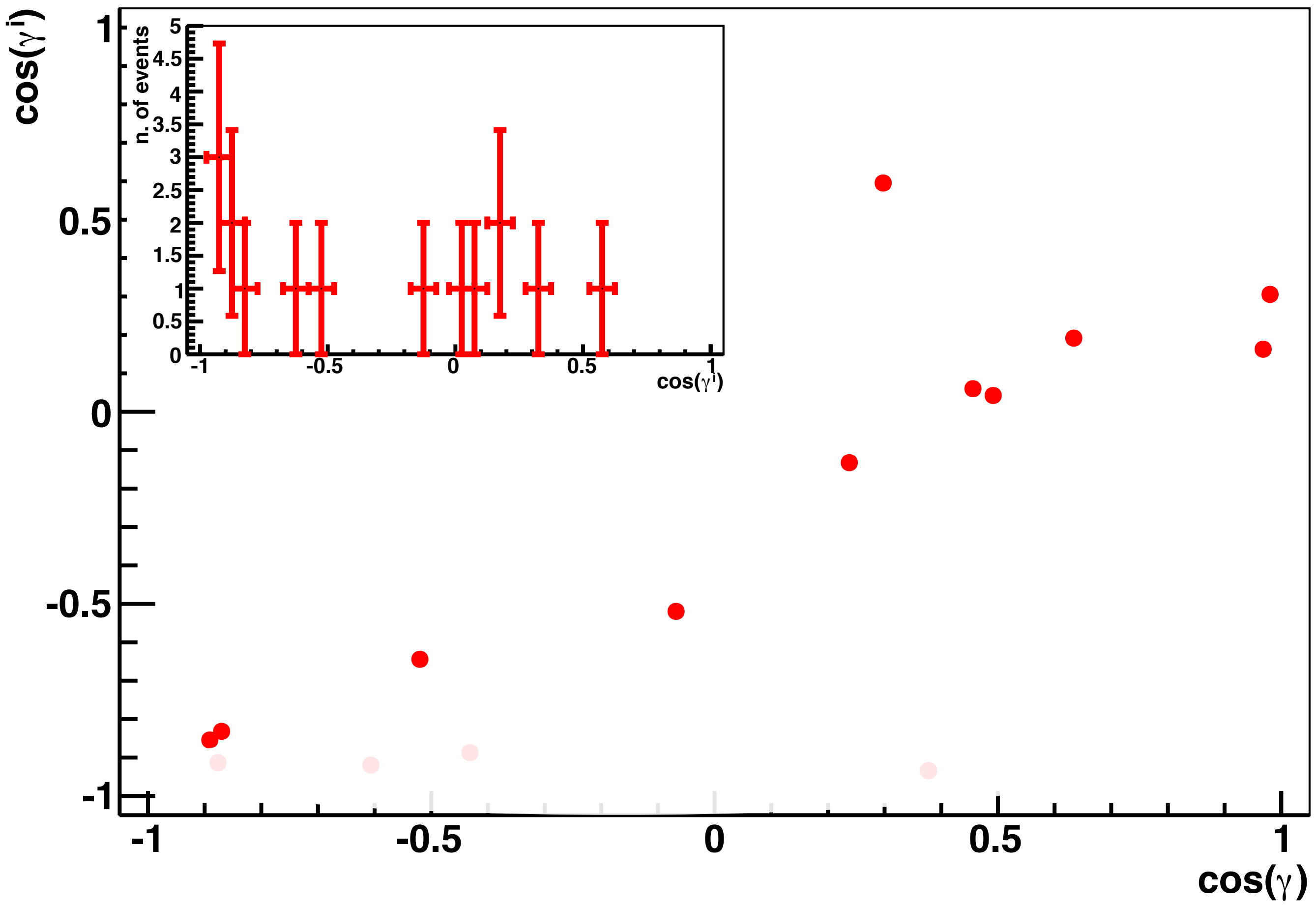
These events appear compatible as originating from SRC pairs through CC QE reactions

Four events (those horizontally aligned in the lowest cos(γi) bin, rather separated from the others) are reconstructed with the pair in a **back-to-back** configuration in the CM frame, cos(γi)<-0.9 and have reconstructed initial momenta $>K_F$

The measured transverse component of the missing momentum in these events is small (≲250 MeV/c).

The bin size includes the effect of the uncertainty in the transfer momentum reconstruction on the measurement of cos(γ_i)

what about the Other (μ^-+2p) events ?



There is no immediate interpretation for the *apparent correlation* of the remaining 11 events.

- Two-step process such as:
  MEC or
  Isobar Currents (IC) involving NN long-range correlated pair in the nucleus are obviously active in two-proton knock-out production

- Other mechanisms like interference between the amplitudes involving one-and two-nucleon currents, subject to current theoretical modelling, can also potentially contribute
- ….

- In all cases, protons can undergo **FSI** inside the residual nuclear system before emerging and propagating in the LAr active detector volume.
- ***In general, however, the emission of energetic, angular correlated proton pairs from FSI appears disfavored***

To be published in the next PRD issue

PHYSICAL REVIEW D 90, 000000 (XXXX)

Detection of back-to-back proton pairs in charged-current neutrino interactions with the ArgoNeuT detector in the NuMI low energy beam line

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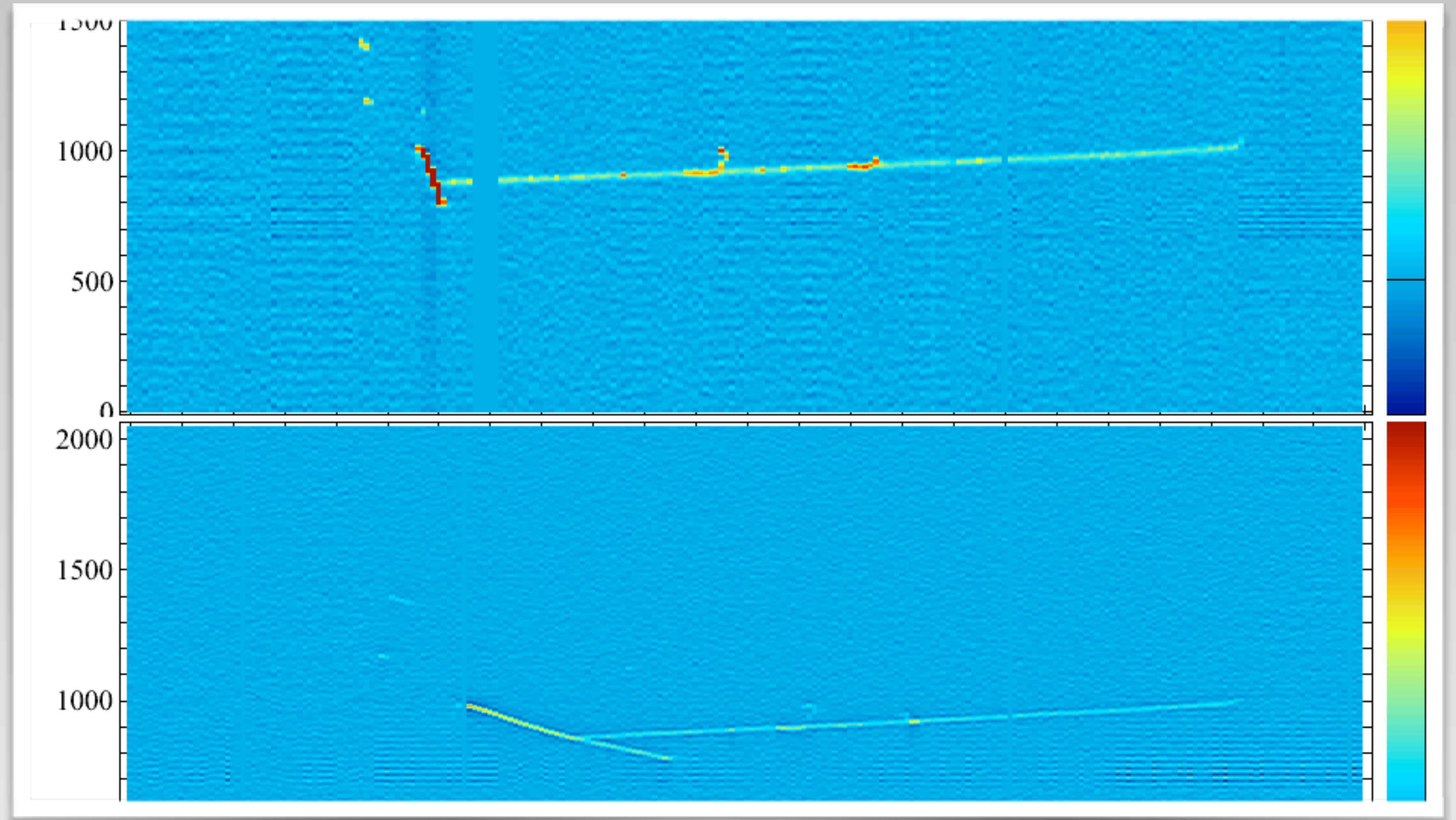
(Received 4 June 2014)

Short range nucleon-nucleon correlations in nuclei (*NN* SRC) carry important information on nuclear structure and dynamics. *NN* SRC have been extensively probed through two-nucleon knockout reactions in both pion and electron scattering experiments. We report here on the detection of two-nucleon knockout events from neutrino interactions and discuss their topological features as possibly involving *NN* SRC content in the target argon nuclei. The ArgoNeuT detector in the Main Injector neutrino beam at Fermilab has recorded a sample of 30 fully reconstructed charged-current events where the leading muon is accompanied by a pair of protons at the interaction vertex, 19 of which have both protons above the Fermi momentum of the Ar nucleus. Out of these 19 events, four are found with the two protons in a strictly back-to-back high momenta configuration directly observed in the final state and can be associated to nucleon resonance pionless mechanisms involving a pre-existing short range correlated *np* pair in the nucleus. Another fraction (four events) of the remaining 15 events has a reconstructed back-to-back configuration of an *np* pair in the initial state, a signature compatible with one-body quasielastic interaction on a neutron in a short range correlation (SRC) pair. The detection of these two subsamples of the collected $(\mu^- + 2p)$ events suggests that mechanisms directly involving nucleon-nucleon SRC pairs in the nucleus are active and can be efficiently explored in neutrino-argon interactions with the Liquid Argon Time Projection chamber technology.

DOI:

PACS numbers: 13.15.+g, 25.30.Pt, 25.10.+s

anything NEW ?!

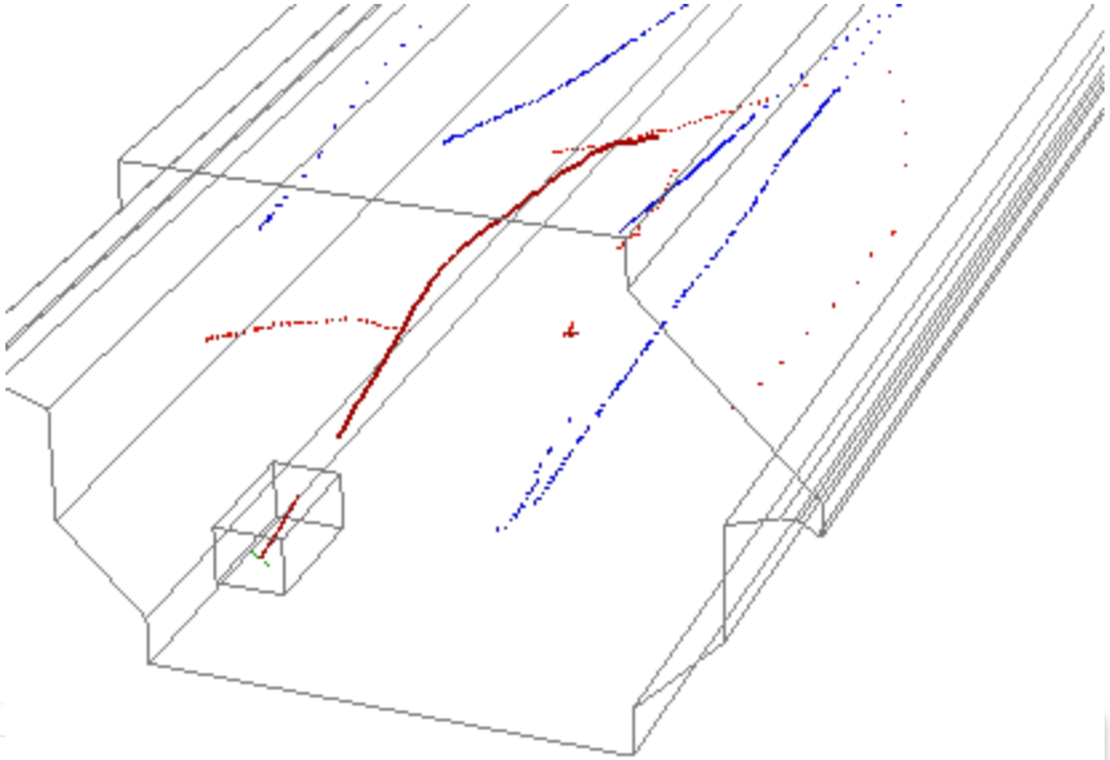


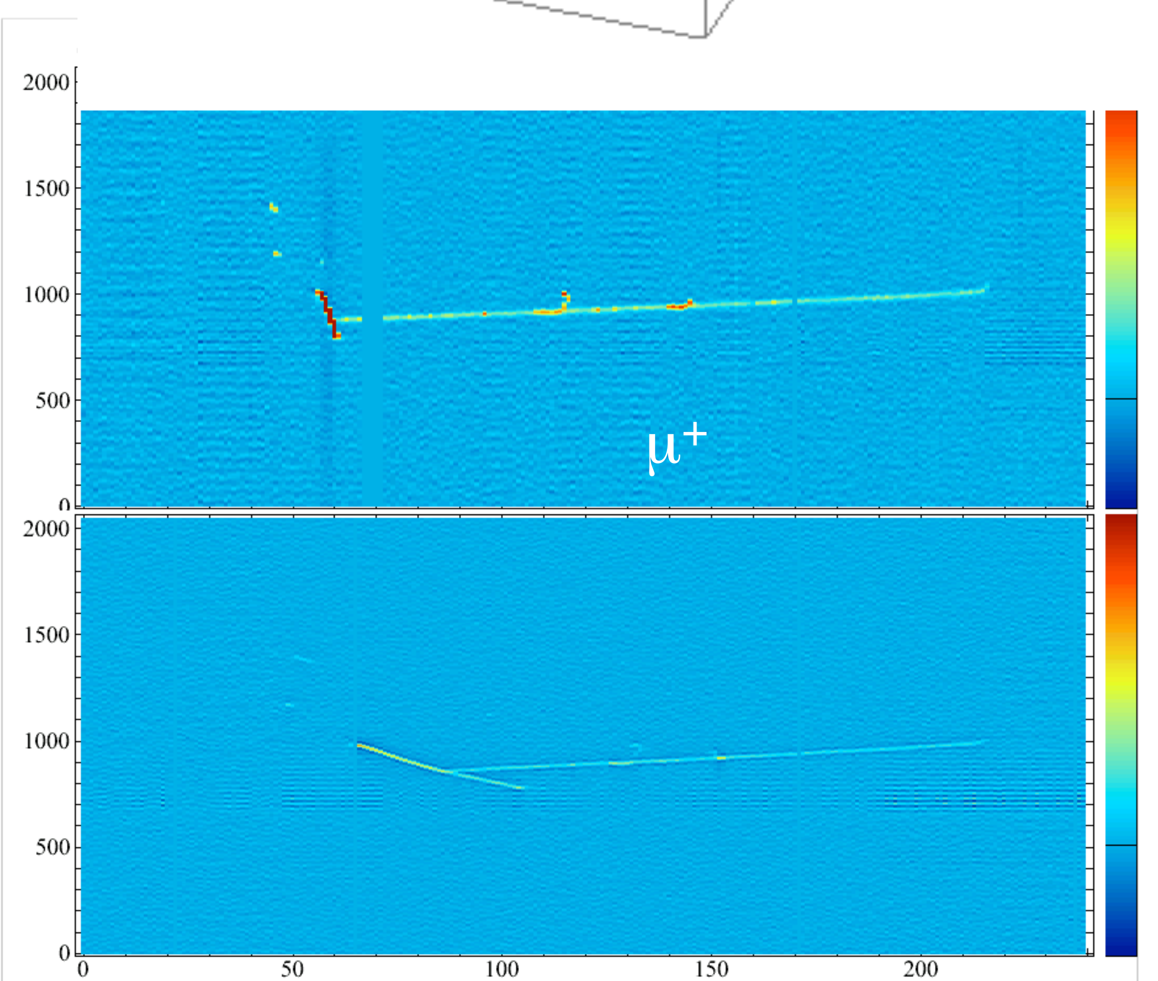
we have found another *puzzling* "Hammer event"…
in the AntiNeutrino event sample:

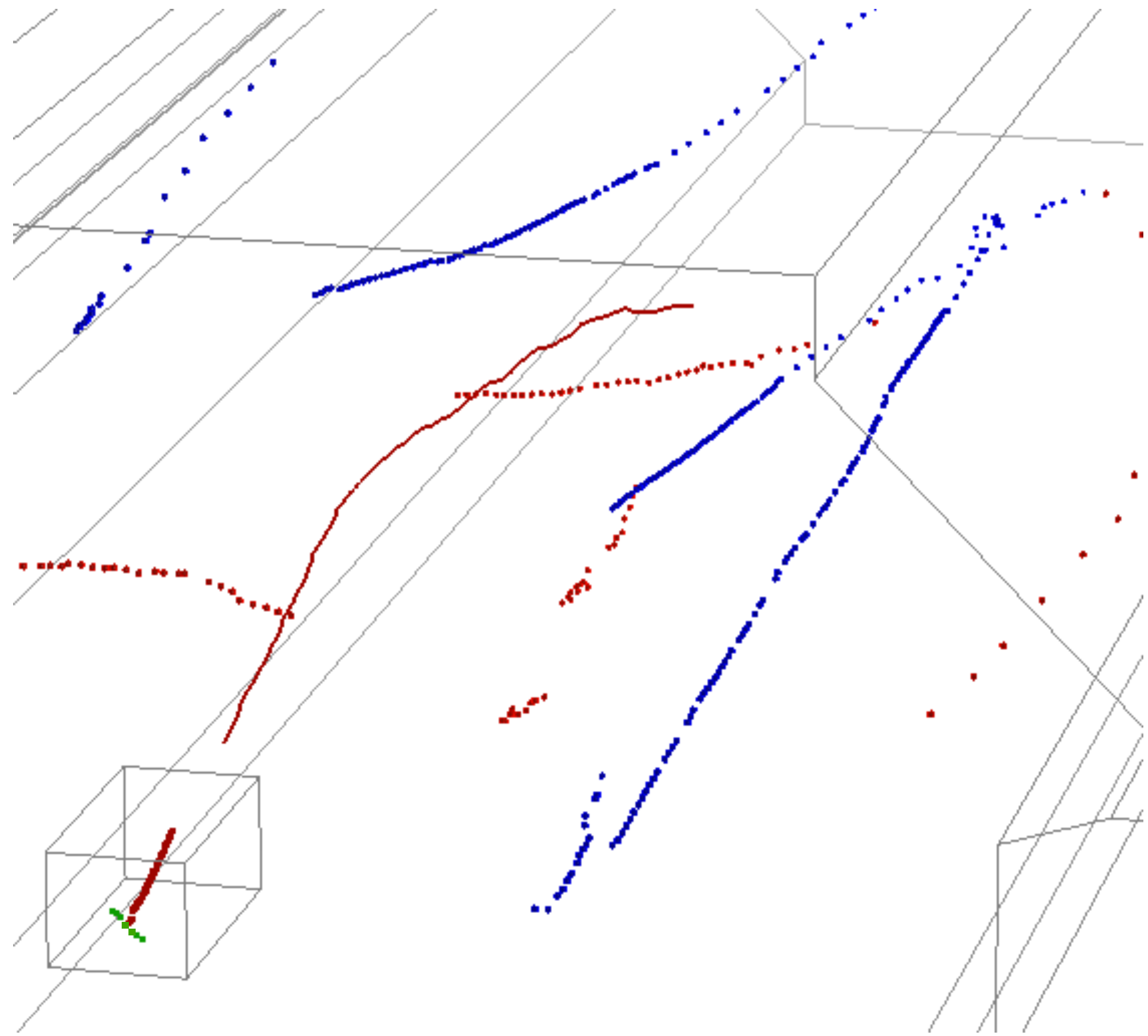
$$\bar{\nu} + Ar \rightarrow \mu^{+} + 2p$$

(showing 3 positive charges in final state)

BACK-TO-BACK PROTON PAIR EVENT MUON TRACK MATCHING IN MINOS ND

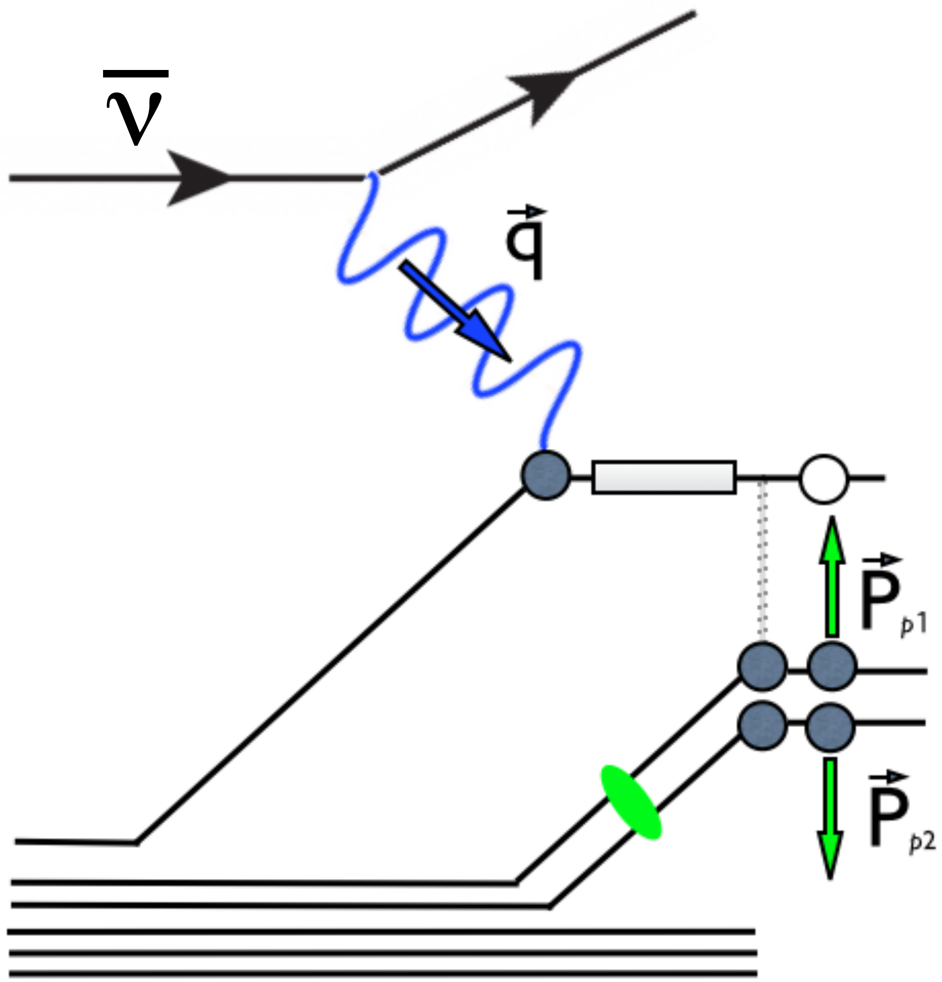


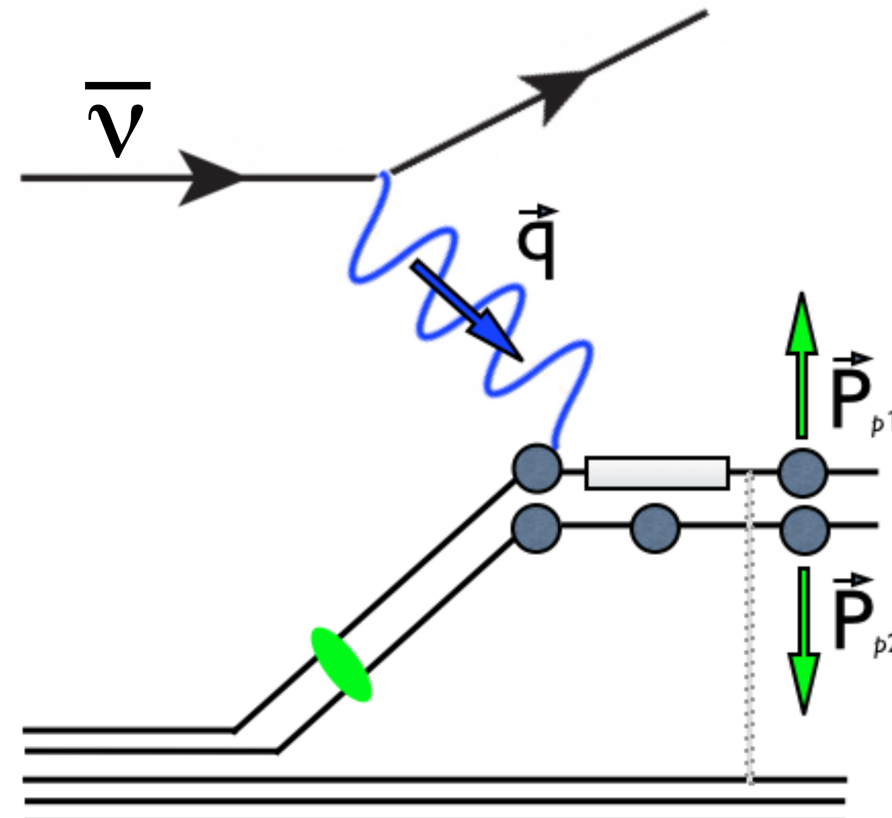




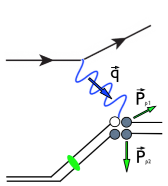
Red (blue): positive (negative) charge tracks determined by MINOS.

exploring possible mechanisms in analogy with neutrino Hammer events





Note: The QE mechanism(on single nucleon in a pair) is undetectable because (np) + W$^-$ → (nn)



The event statistics from ArgoNeuT is very limited (~ 5 months run on the NuMI beam with a 240 Kg active volume LArTPC)

Future LArTPC experiments: MicroBooNE, LAr1-ND…

MicroBooNE estimated events rates (GENIE)

6.6 10^{20} POT exposure of MicroBooNE will provide an event sample of ~57000 CC 0-pion events

LAr1-ND estimated events rates (GENIE)

2.2 10^{20} POT exposure of LAr1-ND will provide an event sample 6-7x larger than will be available in MicroBooNE

CONCLUSIONS

- Topological **CC *0-pion*** sample analysis in ArgoNeuT:
  - First measurements of ***Anti-neutrino cross section on Ar.*** Neutrino cross sections are coming soon
  - Measurements are presented in terms of Eν calculated from the observed ***final-state particle kinematics***

Model independent measurement

  - (μ^-+2p) analysis ➠ ***back-to-back proton events***:
    - suggests that mechanisms directly involving NN SRC pairs in the nucleus are active and can be efficiently explored in *ν-Argon interactions with the LAr TPC technology*
    - accurate and detailed MC neutrino generators are deemed necessary for comparisons with LAr data (with the inclusion of a realistic and exhaustive treatment of SRC in the one- and two-body component of the nuclear current). ***We hope the ArgoNeuT data will encourage more studies in this area.***